AN ABSTRACT OF THE THESIS OF

Gregg A. Lomnicky for the degree of Doctor of Philosophy in Fisheries Science

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Abstract approved: Signature redacted for privacy.

William J. Liss

Factors affecting physical, chemical, and biological characteristics of lakes were investigated through the development of a lake-classification system for 162 lakes in North Cascades National Park Service Complex. A conceptual view of lake development and its relationship to the expression of lake and watershed characteristics was derived. Water quality and biological assemblages of these primarily glacially formed high-mountain oligotrophic lakes were influenced by elevation, lake morphology, and certain watershed characteristics: aspect, vegetation, soils, hydrology, and degree of glacial influence. Lakes continually evolve relative to changes in their watershed environments. A watershed-based, three-level hierarchical classification was created to include 1) lake position relative to the hydrologic crest of the North Cascade Mountain Range, 2) vegetation zone (alpine, subalpine, low elevation forest, high elevation forest), and 3) basin origin. Hydrologic crest position differentiated broad-scale climatic differences in precipitation and air temperature. Vegetation zones reflected the localized geology (soil maturation) and climate (precipitation, aspect). Morphogenetic class identified differences in lake morphology, landscape position, and potential for persistence, and were unequally distributed across vegetation zones with forest zones most diverse. Time of ice-out increased from low-forest lakes to alpine lakes; eastslope lakes iced-out earlier. Epilimnetic temperature was warmest in low-forest lakes and coolest in alpine lakes. Classification did not clearly order lakes relative to chemical characteristics, though westslope low-forest lakes differed significantly from other lake classes and were most productive. Little seasonal or annual variation for most chemical characteristics were found. However, chemical differences did mirror environmental and physical differences between lakes. High phosphorus levels separated glacially influenced lakes. Total Kjeldahl-N and total phosphorus concentrations decreased with increasing lake depth. For a given flushing ratio, Kjeldahl-N decreased from low-forest to alpine zones. Depth and vegetation class ordered the diversity and composition of phytoplankton, zooplankton, and benthic macroinvertebrate assemblages. Nutrients, conductivity, pH, alkalinity, and cations were correlated with phytoplankton and zooplankton assemblages. Non-native trout presence was associated with large, deep ($\geq$ 3 m) lakes.

Lake Classification in the Glacially Influenced

Landscape of the North Cascade Mountains, Washington, USA

by

Gregg A. Lomnicky

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Lake, loch, lough, mere, tarn, plash, broad, pond, sump, slab, linn, tank, puddle, well, artesian well, standing water, dead water, sheet of water, mill pond, ditch dyke, reservoir, mill race, albercera, piscina, hog wallow, buffalo wallow, marsh, swamp, bog, sump, slough, mud wash, jhil, vlei, squash, aquarium, cistern, cesspool, sewer, sink, water-hole, inland sea, bayou, ox-bow.

Rogets Thesaurus

INTRODUCTION

Numerous classifications of lakes have been developed during the past century, each representing an effort to better understand variability within and among lake systems. Busch and Sly (1992) identified many approaches in their review of systems to classify the aquatic habitat of lakes. Some researchers focused on physical characteristics such as origin, shape, mixing, location and morphometry (Rawson 1955, Hutchinson 1957, Larkin and Northcote 1958, Pennak 1958, Lewis 1983, Canfield and others 1984, George and Maitland 1984). Many have differentiated lakes based on chemical characteristics including total dissolved solids, pH, bicarbonate alkalinity, and trophy (Stockner and Benson 1967, Vollenweider 1968, Larson 1970, Kemp 1971, Schneider 1975, Pitblado and others 1980, Chapra and Dobson 1981). Still others have identified differences in lakes based on biological characteristics including plankton, macrophytes, zooplankton, benthic macroinvertebrates and fish (Thieneman 1909, Nygaard 1949 , Rawson 1956, Brundin 1958, Round 1958, Jensen and Van Der Maarel 1980, Sprules 1980, Harvey 1981, Tonn and Magnusson 1982, Rott 1984). In an attempt to deal with the complex nature of these systems, some researchers have integrated combinations of physical, chemical, or biological characteristics through the characteristics through the development of a Trophic State Index (Carlson 1977), a Morpho-Edaphic Index (Ryder 1965, Ryder and others 1974), and a nutrient flux index (Schindler 1971).

Classifications can be organized into three general categories: functional, environmental, and genetic lake classifications (Welch 1978). Functional approaches, which tend to be the most common approaches attempted, focus on describing dynamic properties of lakes such as water temperature, water chemistry, and nutrient flux. These approaches generally require many sampling occasions on site. Welch (1978) suggests that environmental classifications focus on descriptive properties such as the terrestrial environment and lake morphology, stable properties that lend themselves to identification via remote sensing such as aerial photography. Many land-based classifications take this form (Bailey 1976, Lotspeich and Platts 1982, Omernik and Gallant 1986). Genetic classifications (Hutchinson 1957, Wetzel 1983) are based on lake origin and may not offer much information on current physical, chemical, or biological processes such as flow, microclimate, nutrient status or size that are occurring in and around the lakes. However, genetic classifications may have utility when used with descriptive and functional data, because lake and landscape formation are closely related (Welch 1978).

A variety of classifications have been developed to meet diverse objectives. The utility or design of each classification depends upon the specified objectives, local situations, and the geographic scale of interest. Objectives may range from basic research to application in resource management and/or satisfying legal mandate. Each region is unique, and, thus, criteria for the development of many classification schemes are locally dependent. For example, a number of regional typologies have been developed for areas that may differ with respect to glaciation, tectonics, mass wasting, lithology and major vegetation assemblages (Jarnefelt 1958, Larkin and Northcote 1958, Margalef 1958, 1975, Pennak 1958, Rawson 1961). Nationally, classifications and inventories may be the result of federal objectives that are very different than more specific, localized classifications based on scale or political differences.

Within the North Cascades, water quality, physical habitat, and biological structure of high-mountain lakes may be influenced by elevation, watershed characteristics, and lake morphology. Research from other regions supports this hypothesis: Pennak (1958) concludes that elevation influenced water quality and structured biological communities in northern Colorado lakes, while Mosello and others (1990) report that water chemistry in alpine lakes of North West Italy is influenced by lithology, vegetation, and amount of atmospheric deposition. Larkin and Northcote (1958) make similar findings in British Columbia, determining that geology, climate and interaction between these two components influences total dissolved solids in lakes, which they identified to be an index of production. Stewart and Haugen (1990) conclude that lake morphometry is an important variable in determining ice-up and ice-free dates for lakes from heat-budget effects. Hoffman and others (in press)) reported that both abiotic (mineral substrate) and biotic (organic material for epilimnetic habitat, macroinvertebrates) characteristics of lakes in the North Cascades were influenced by terrestrial characteristics and processes. Pechlaner (1971) concludes that primary production and phytoplankton biomass in high-mountain, oligotrophic lakes are affected by lake hydrology, temperature, winter snow cover and water chemistry, while Rankin and Ashton (1980) report zooplankton biomass to be correlated with elevation, mean depth, precipitation, and total dissolved solids. Lomnicky and others (1989) provide a conceptual framework for these interrelating processes and characteristics arguing that lakes interact with climate and watershed features. Additionally, they describe the influence that lake morphometry together with climate and watershed features has in the development of physical, chemical, and biological characteristics of lakes at the spatial scales found in North Cascades National Park Service Complex (NOCA). Consistent with the conceptual framework developed by Lomnicky and others (1989), Larson and others (1994) report that limnological characteristics of high-mountain lakes result from complex interactions of climatic conditions; watershed characteristics including geographical location, aspect, surface area, elevation, geology, hydrology, soil and vegetation; and lake morphometry.

Study Area

NOCA, which is located in north-central Washington along the Canadian border (Figure 1), contains 162 lakes that are considered important to fisheries management by National Park Service and Washington State fishery biologists. The rugged topography spans the crest of the North Cascades; many land forms are still being altered by processes such as faulting, uplift, and subsidence (Press and Siever 1982, McKee 1972). The park, encompassing 204,000 ha, is separated into two geographical regions, westslope and eastslope. Westslope drainages empty into Puget Sound and eastslope systems flow into the Columbia River. Park elevation ranges from 150 m above mean sea level to 2770 m at Mt. Logan on the westslope and 335 m (Lake Chelan) to 2400 m (Mt. McGregor) on the eastslope (GS 1974). NOCA encompasses a diversity of climatic and vegetative zones from warm, moist lowland forests on the westslope, to cold desiccated alpine environments found on the eastslope and westslope, and dry lowland environments east of the crest.

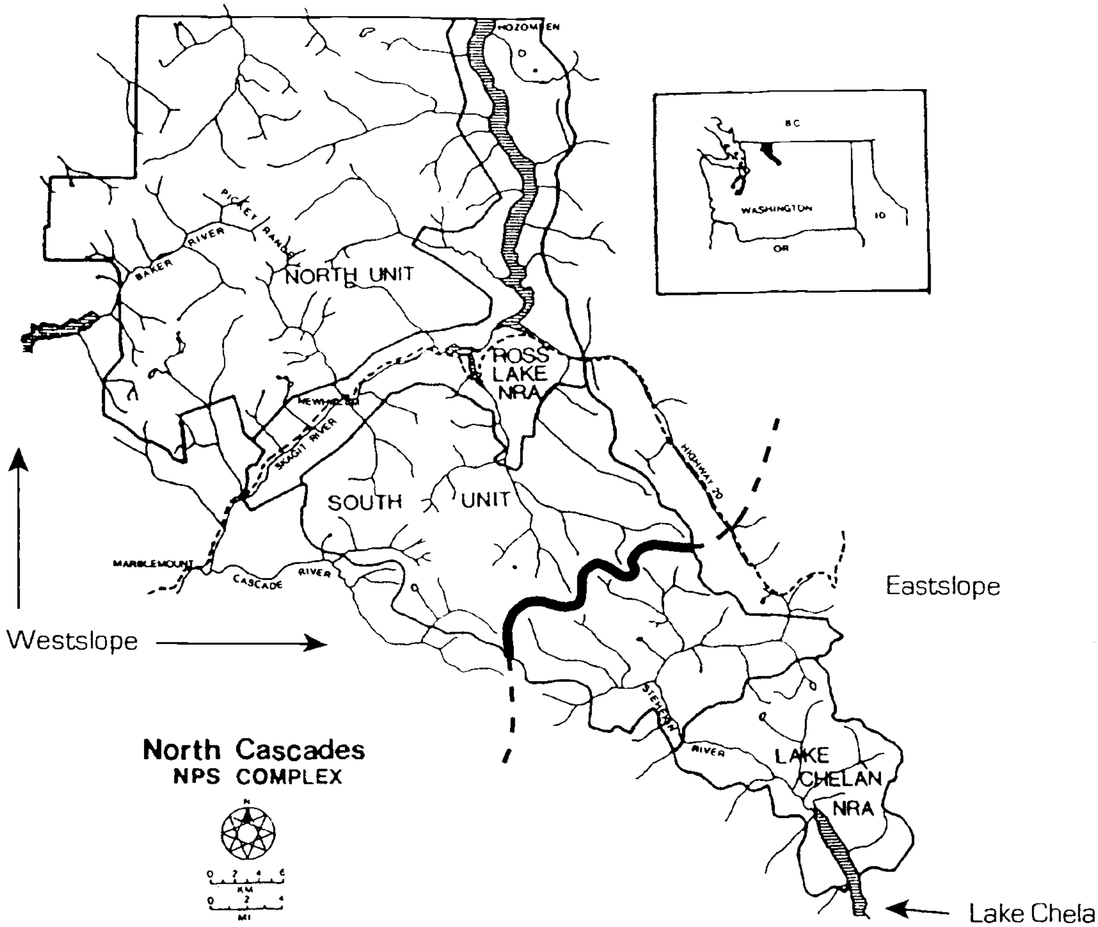


Figure 1. Location of the North Cascades National Park Service Complex in Washington. Westslope/Eastslope: relative to the hydrologic crest. Bold line represents the crest.

At a regional scale, NOCA lakes may be considered diverse in many physical attributes (Lomnicky and others 1989) because they differ in geologic and climatic setting, age, origin, elevation, aspect, extent of glacial influence, vegetational setting, morphometry including size and depth, and many other characteristics. However, from a global perspective (Hutchinson 1957, Goldman and Horne 1983, Wetzel 1983), these lakes can be considered much more similar using the same criteria. Primarily high-mountain lakes of glacial origin, most can be identified as oligotrophic based on nitrogen and phosphorous concentrations of the lake water (Likens 1975).

Goals and Objectives

The goal of this study was to better understand the similarities and dissimilarities among mountain lake systems in NOCA relative to physiographic characteristics (climate, topography, origin, geology, vegetation) of the terrestrial environment and lake morphometry.

The objectives were

1. Develop a hierarchical classification incorporating physiographic (geological, vegetative and climatological) attributes of the terrestrial environment.
2. Use the classification to identify the diversity of lake types (classes) parkwide.
3. Determine physical and chemical properties of lakes and relate these to physiographic characteristics of the terrestrial environment through classification.
4. Test the utility of this classification for providing ecologically meaningful generalizations regarding the NOCA lake systems.

To accomplish these objectives, existing land and lake classification approaches were reviewed to assess their utility for this research; existing land classifications were inappropriate. Bailey (1976) and Omernik and Gallant's (1986) ecoregion classification identifies the entire Cascades as a single region. These small scale approaches were too general to help classify lakes at NOCA. Many previous classification schemes have identified linkages between lake and watershed characteristics and processes, but these schemes tend to deal either with geographic regions having a greater physical and chemical diversity among lakes (Vollenweider 1968, Ryder and others 1974, Carlson 1977) or a more uniform environment (Schindler 1971) than exists at NOCA. A different approach was necessary for the conditions found at NOCA.

CONCEPTUAL FRAMEWORK

A conceptual view of lake development and its relationship to the expression of lake and watershed characteristics was developed to provide context for this classification approach.

Lakes, like streams, are products of their surrounding watersheds, and lakes reflect the outcome of numerous processes. Likens and Borman (1974) recognized that a linkage exists between land and water though they did not classify streams or lakes. Others have taken a stronger view that water resources are embedded in land ecosystems (Welch 1978, Warren 1979, Lotspeich and Platts 1982, Frissell and others 1986, Swanson and others 1988). Land ecosystems or watersheds are the environments of lakes (Warren 1979, Aber and Melillo 1991, Larson and others 1994), and the influence of watershed characteristics (slope, geology, aspect, elevation, vegetation) determines the rate of nutrient loading, sediment delivery, water quantity and timing (peak flows, seasonal low flows) , and biologic complexity in streams and lakes (Gorham 1961, Livingstone 1963, Ohle 1965, Vollenweider 1968, Schindler 1971, Hilton 1979, Teti 1984, Hem 1989, Mosello and others 1990, Hoffman and others in press).

The expression of physical, chemical, and biological attributes—anything measurable—may be described as a performance of the lake or surrounding watershed (Warren 1979, Lomnicky and others 1989). Examples include watershed area, vegetation, lake temperature, surface area and depth, and densities and types of organisms present. Geologic and climatic processes directly influence substrate and physical and chemical performances of lakes (Hem 1989), and these processes indirectly influence watershed structure (relief, aspect, soil maturation and vegetation development) (Franklin and others 1988) and lake morphometry (Rawson 1955, Hutchinson 1957).

Lakes are dynamic systems that continually evolve or develop relative to changes in their watershed environments. For example, a lake recently exposed by glacial recession would likely have quite different chemical and physical characteristics than an otherwise similar lake formed by the same processes and exposed thousands of years ago. Or, if conditions in the watershed were to change, say it was much warmer last year than this year, then this change in lake environment may be reflected in some kind of change in many seasonal lake performances such as stratification, date of ice-out, development of biological assemblages, and production of phytoplankton.

These ideas can be articulated theoretically by introducing the concept of capacity developed by Warren and others (1979). They propose that the performance of a system (anything that can be quantified) at any stage in its development is jointly determined by present environmental conditions and the realized capacity of the system at that developmental stage. Realized capacity can be envisioned as all possible lake performances (e.g. temperature, clarity, trophy, depth, etc.) that may occur at the present time, in all possible environments. It is contingent upon the present organization of the system, that is how the system components are put together. Thus, the lake performances we presently observe are jointly determined by the present organization of the lake system and the present developmental environment of the system. System development (i.e., its change in organization through time) can be conceptualized as being determined by the development of the environment of the system and the system's potential (original) capacity, where potential capacity is all possible developmental trajectories that a system could take if exposed to all possible environments.

Watersheds, lakes, and the biological communities found in lakes can be thought of as codeveloping systems (Figure 2) that may be considered over geologic, annual, and seasonal time frames. In the North Cascades mountain range, the development of watersheds over geologic time has involved the working and reworking of the watersheds and lake basins by glaciers, downcutting by stream channels, developing of soils from bedrock and till, and the establishing and developing of vegetation assemblages. Moreover, the watersheds of this region are still developing. Recent glacial recession had led to the formation of new lakes. Whether watershed changes are viewed over short term or long term, lakes and streams will, to some extent, reflect these changes. Both primary and secondary plant-assemblage succession, which occurs with succession reset anew following fire or other disturbance, and human cultural impacts—whether from far away sources of atmospheric pollution or change induced directly on-site—are potential sources for watershed change. The development of lakes through time and the characteristics they exhibit at any particular time are determined, at least in part, by the development and characteristics of their watershed environments (Figure 2, a and b). Theoretically, the development of biological communities inhabiting lakes must reflect changes in the chemical and physical characteristics of the lake habitat (Figure 2c). Therefore, the aquatic community, the lake it inhabits, the watershed in which the lake is embedded, and the system of watersheds within a biogeoclimatic region can be viewed as mutually influencing, codeveloping systems.

Figure 2. The watershed, lake, and community are conceptualized as codeveloping systems. Each system develops according to its potential capacity and changes in its environment. The environment of the watershed is the biogeoclimatic region. The watershed forms the environment of the lake. The lake habitat is the environment of the community, the community and its habitat together forming the lake as a whole. Each state or stage in development of the watershed (a), the lake (b), and the community (c) are designated as Wij, LSij, and LHij, respectively, where i designates developmental environment and j designates developmental state. For example, W11, W12, W13 are three consecutive stages of development of the watershed in biogeoclimatic environmental context (a). If the watershed develops in this way, then the lake, influenced by watershed changes, will develop through states LS11, LS12, LS13 (b). Development of the lake entails concordant development of the lake habitat (LH11, LH12, LH13) and the codevelopment, the watershed, the lake, and the community exhibit observable performances (p).

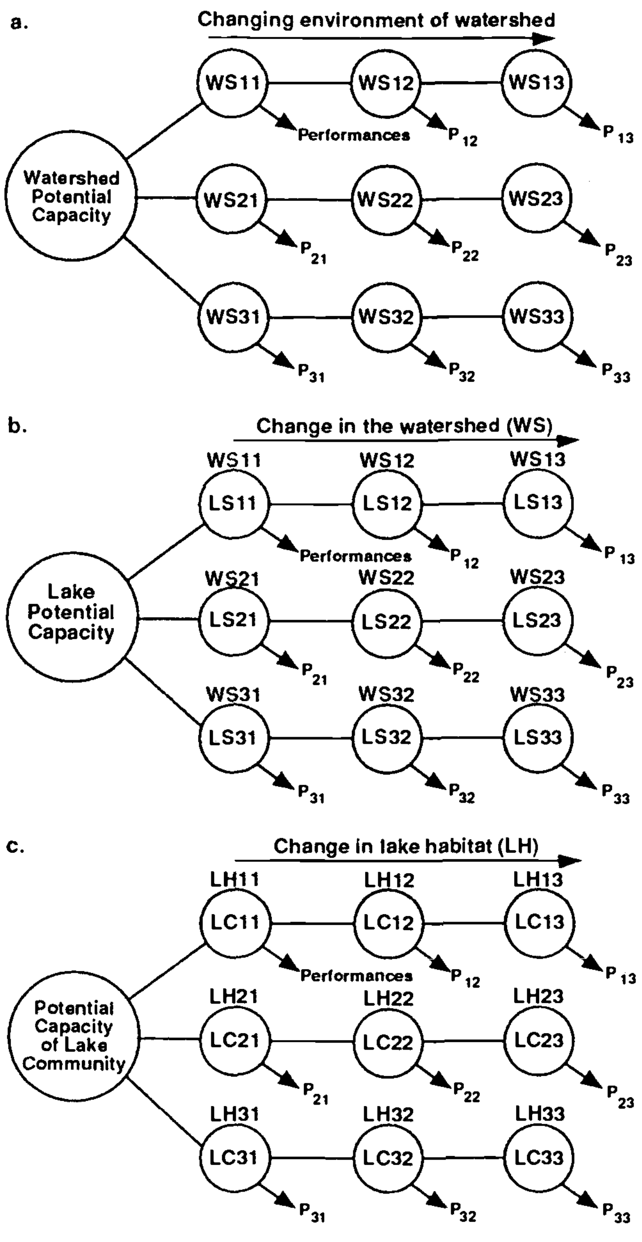

a.
Changing environment of watershed
Watershed Potential Capacity
WS11
WS12
WS13
WS21
WS22
WS23
WS31
WS32
WS33
Performances
P 12
P 13
P21
P22
P23
P31
P32
P33
b.
Change in the watershed (WS)
Lake Potential Capacity
WS11
WS12
WS13
LS11
LS12
LS13
WS21
WS22
WS23
LS21
LS22
LS23
WS31
WS32
WS33
LS31
LS32
LS33
Performances
P 12
P 13
P21
P22
P23
P31
P32
P33
c.
Change in lake habitat (LH)
Potential Capacity of Lake Community
LH11
LH12
LH13
LC11
LC12
LC13
LH21
LH22
LH23
LC21
LC22
LC23
LH31
LH32
LH33
LC31
LC32
LC33
Performances
P 12
P 13
P21
P22
P23
P31
P32
P33

Figure 2.

Lake and Watershed Development at NOCA

Relations among components of mutually influencing, co-developing watersheds and lake systems are complex and highly interconnected. Climatic and geomorphic processes such as tectonics and glaciation mold a geologic template that influences lake evolution and development. Geologic and climatic processes directly or indirectly influence potential and realized physical and chemical performances of lakes through their impact on watershed structure (Hilton 1979, Aber and Melillo 1991), lake morphometry (Rawson 1955), rate of soil maturation (Buol and others 1973, Ollier 1984), and vegetation (Mosello and others 1990) (Figure 3). Developmental processes which ultimately constrain and define classes of lakes at NOCA , and thus their performances, are spatially and temporally dependent (Table 1). Temporal and spatial scales appropriate for developmental processes and evolutionary events occurring at NOCA are given in Table 1. Developmental processes that are constrained or enhanced by climate include drainage network development, organic material accumulation, and sedimentation (Table 1). These processes affect the path and flux of water movement through watersheds which, in turn, affects nutrient concentrations in lakes.

NOCA lakes are predominantly of glacial origin; therefore, their development has generally initialized with glacial ablation. NOCA lake and watershed development since that time can be understood as progressing through a continuum from our present-day alpine to subalpine and forest states given enough time and favorable location. Generally, under the present regional climatic conditions, alpine watersheds and lakes exist at the highest elevations while forest systems are at the lowest elevations. Subalpine systems occur between the two.

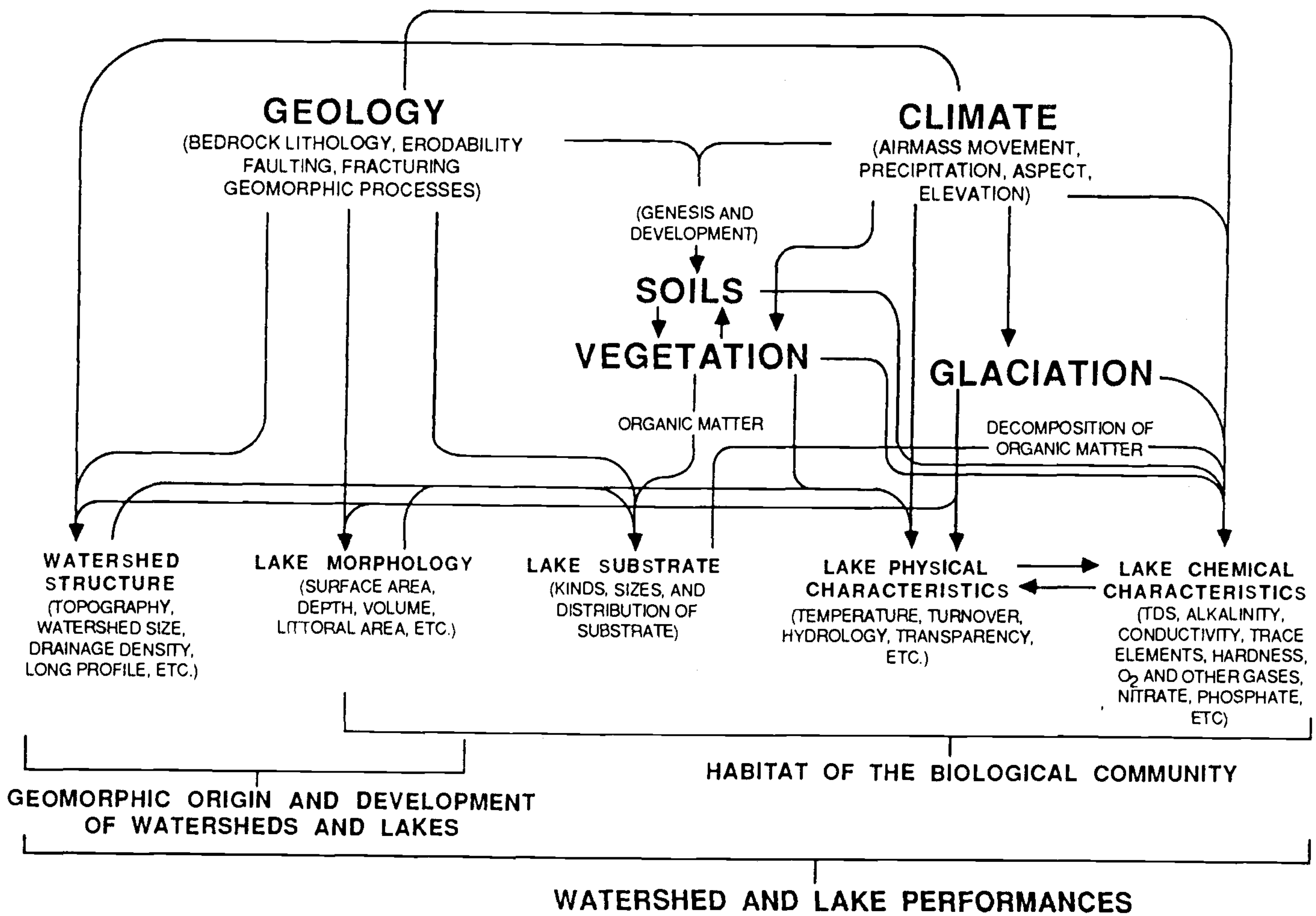


Figure 3. Interrelationships among components of watersheds and lakes. Geology and climate form the developmental environment for soils, vegetation, and glaciation. Watershed structure, lake morphology and substrate, and lake physical and chemical characteristics are performances of this developmental environment.

Table 1. Processes or events controlling systems on different spatial and temporal scales in North Cascades National Park Service Complex.

System level	Area spacial scale (km^2)[a]	Evolutionary events[b]	Developmental processes[c]	Time scale of continuous potential persistence (years)[d]
Regional (Park)	10^3	Tectonic uplift (orogeny); subsidence; volcanism; Igneous plutonic metamorphism.	Planation (chemical and mechanical weathering). Drainage network development.	10^5–10^6
Major Drainage Units (Skagit, Stehekin, Chiliwack/Nooksack)		Cordilleran ice sheet advance; severe glacial erosion in different lithologies of major watersheds; stream capture.	Planation (chemical and mechanical weathering). Drainage network development.	10^4–10^6
Drainage Subunits (major tributaries of major drainage units)	10^1–10^2	Pleistocene (Fraser) glaciation Glacial landforms: Erosion trough valley, col, cirque hanging valley Deposition moraines (lateral, terminal) alluvial infilling Faulting (Ross Lake, Straight Creek)	Drainage network development; denudation; glacial drift agradation (till, stratified drift, outwash)	10^4
Lake Watershed	10^{-1}–10^1	Neoglaciation (alpine glaciation); glacial erosion and deposition. Lake formation: trough, kettle, cirque, scour slump, moraine, fault Landslides, slumping. Local faulting.	Glacial transport of sediments raveling; frost riving. Mass wasting-talus skree; organic material accumulation soil formation.	10^3–10^4
Lake	10^{-1}–10^1	Lake evaporates, freezes up, fills up, de-ices. Landslides, slumping. Macrophyte establishment.	Allochthonous inputs organic and mineral. Sedimentation. Increasing nutrient concentrations and biological complexity.	10^1–10^4

[a]Spacial scales follow Lotspeich & Platts (1982).
[b]Evolutionary events change potential capacity, i.e., (extrinsic forces that create and destroy systems at that scale). (defined following Frissell and others 1986)
[c]Developmental processes are intrinsic, progressive changes following a systems genesis in an event. (defined following Frissell and others 1986)
[d]Appropriate to geologic/climatic time frame of NOCA.

Factors Affecting Development

The rate of watershed and lake development—and the expression of physical and chemical parameters—can be affected by climatic regime, geology, and disturbance factors. Development may be arrested or reversed at any stage or state because of prevailing or changing climatic conditions. Elevation, latitude, basin aspect, and the proximity to glaciers influence local climate in each lake basin (Table 1). These varying conditions may affect the rate, or potential, for further development. For example, two lakes at the same elevation on a mountain may have differing aspects resulting in very different localized climates. West-facing lake basins, with warmer afternoon sun and increased precipitation relative to east-facing basins, may have progressed to a forest stage while the east-facing basin still has alpine characteristics. As a result, elevation is just one factor determining local climate in a mountainous environment.

Disturbance regimes such as fires and annual snow events can maintain a particular developmental state by 'resetting' successional vegetation trajectories. In the subalpine zone, snow period minimizes survival of tree seedlings thus prohibiting forest states from developing. Additionally, plant-assemblage succession may be reset following fire or other disturbance.

LAKE CLASSIFICATION

Classification Rationale

Classification provides a means to order systems having common properties and similar developmental processes. Variables used for classification should be highly determining of system performances (Warren 1979) . Thus, variables used to define and classify systems hierarchically must be appropriately scaled to the space-time frame of the systems composing each hierarchical level (Frissell and others 1986). Because of the high degree of influence and complexity that watersheds provide for lake and stream physical, chemical, and biological characteristics (Warren 1979, Aber and Melillo 1991, Larson and others 1994), classification of lakes to identify differences in communities based on their developmental environment should proceed from the top downward, defining and classifying first biogeoclimatic regions or systems of watersheds, then individual watersheds or subunits, and finally the lakes within these subunits. Each preceding level in the hierarchy forms the environment of lower levels, influencing and imposing both geomorphic and geographic boundary constraints on performances and capacities of objects at the next lower level. Thus by classifying one hierarchical level we have automatically classified the environment of the next lower level (Warren 1979, Frissell and others 1986). This approach facilitates identification and definition of appropriate spatial scales of concern for research inquiries, and provides insight to appropriate temporal scales associated with each spatial scale.

From this top-down perspective, it may not be appropriate to classify lakes solely on the basis of such performances as temperature, phosphate levels, turbidity, or even kinds of biological species because these and many other lake performances are likely to shift with annual and seasonal changes in conditions in watersheds and lakes. Furthermore, there can be great difficulty in measuring these performances—and great monetary costs incurred—for tens or hundreds of lakes located in remote areas, especially if repeated measurements must be made to account for seasonal change. Therefore, to classify lakes at NOCA, variables were selected that relate to, underlie, and determine the patterns of change in physical, chemical, and biological performances that might exist over seasonal, yearly, and decadal cycles of variation. Thus, an attempt was made to classify lakes based on their potential capacities.

An additional logistical constraint imposed on this research to classify all park lakes was that the collected data for each selected variable needed to be obtained without onsite sampling because time, money and other objectives precluded a complete parkwide survey. However, onsite sampling of some lakes was necessary to determine the appropriateness of selected classification variables and to test the utility of the classification.

Based on the literature, the variables selected as most appropriate and useful for this classification approach were bedrock material, climate, glacial influence, vegetation, and morphology of the lake and watershed.

Classification Parameters

Geology

Several geological processes have contributed to the present land forms of the Cascades Region of northern Washington. Subsidence and underthrust by the Pacific plate continues to bring oceanic material toward the west coast of North America

(Press and Siever 1982). The origin of much of the North Cascades lithology is accretion of an island continent that existed in the eastern Pacific Ocean (Alt 1984). Accretions of these microcontinents have led to the formation of the Okanogan, North Cascade, and Olympic mountain ranges, making Washington a mosaic of metamorphosed, sutured, crustal material.

Knowledge of the emplacement and evolution of these large-scale geologic formations in the North Cascades provides insight for the influence this complex lithology has on climatic weathering of the parent rock material, as well as the soil and the drainage-system development. Steep basins with minimal soil and vegetation development are the consequence of the continued orogeny of this geologically young mountain range. Stream density is minimal, and extensive areas of numerous watersheds and lake catchments are covered by angular blocks of talus. These processes ultimately influence the limnological features such as lake morphometry—within lake mineral and organic substrate composition, and potential rate of lake development—including ontogeny and water chemistry (Table 1, Figure 3).

Hard crystalline bedrock, primarily gneiss and granite (Misch 1977), underlies most of the region though some sedimentary and volcanic outcroppings are locally important. Regional uplifting, which initially formed the North Cascades mountains in the Cenozoic 50 million years ago, has created a base template that is highly jointed, faulted and fractured (Misch 1977). Extrusive magma, which originated from the down-thrusting Pacific plate, was given new life and form in the Cascades while intrusive magma altered existing land forms.

The North Cascades are divided into three north-south trending regions which are separated by two major high-angle strike faults (Misch 1966). Straight Creek Fault on the westslope and Ross Lake Fault zone on the eastslope are of Late Cretaceous and Early Tertiary origin. Individually, from west to east, these regions are known as the western foothills region, the Composite Chilliwack Batholith, and the Methow Graben. The westslope contains portions of all three regions while the eastslope is underlain by the Chilliwack Batholith. Collectively, these three regions represent the North Cascades Thrust system (Harris and Tuttle 1983).

The western foothills region is composed of metamorphic, Late Paleozoic and Mesozoic, sedimentary and volcanic rocks (Figure 4). These formations include the Shuksan Greenschist, Darrington Phyllite, Chuckanut Formation (principally sandstones), and the Chilliwack Group (alternating volcanic and sedimentary rocks).

Formations of the Chilliwack Batholith region—or Skagit Crystalline Core—include the Cascade River Schist, Skagit Gneiss, Eldorado Orthogneiss, Gabriel Peak Orthogneiss (a younger less metamorphosed gneiss), and various plutons including the granitic Chilliwack Batholith (Misch 1966).

East of the Ross Lake fault, the Chilliwack Composite Batholith is again exposed. Schists and granites compose other formations of the Methow Graben that are found within the park. One example is the Black Peak Batholith which has originated and developed with movement of the Ross Lake Fault (Figure 4) and is an area considered to have active faulting (Misch 1977).

Glaciation

In the last 50,000 years, climatic processes including glaciation have worked and reworked the geologic template. Pleistocene glaciation spread into Washington from Canada as two lobes, the Puget lobe west of the Cascades and the Okanogan lobe on the east. During the Fraser period of glaciation, 25,000–10,000 years ago (Crandell 1965), the Skagit, Stehekin, and Cascade river valleys were broadened and

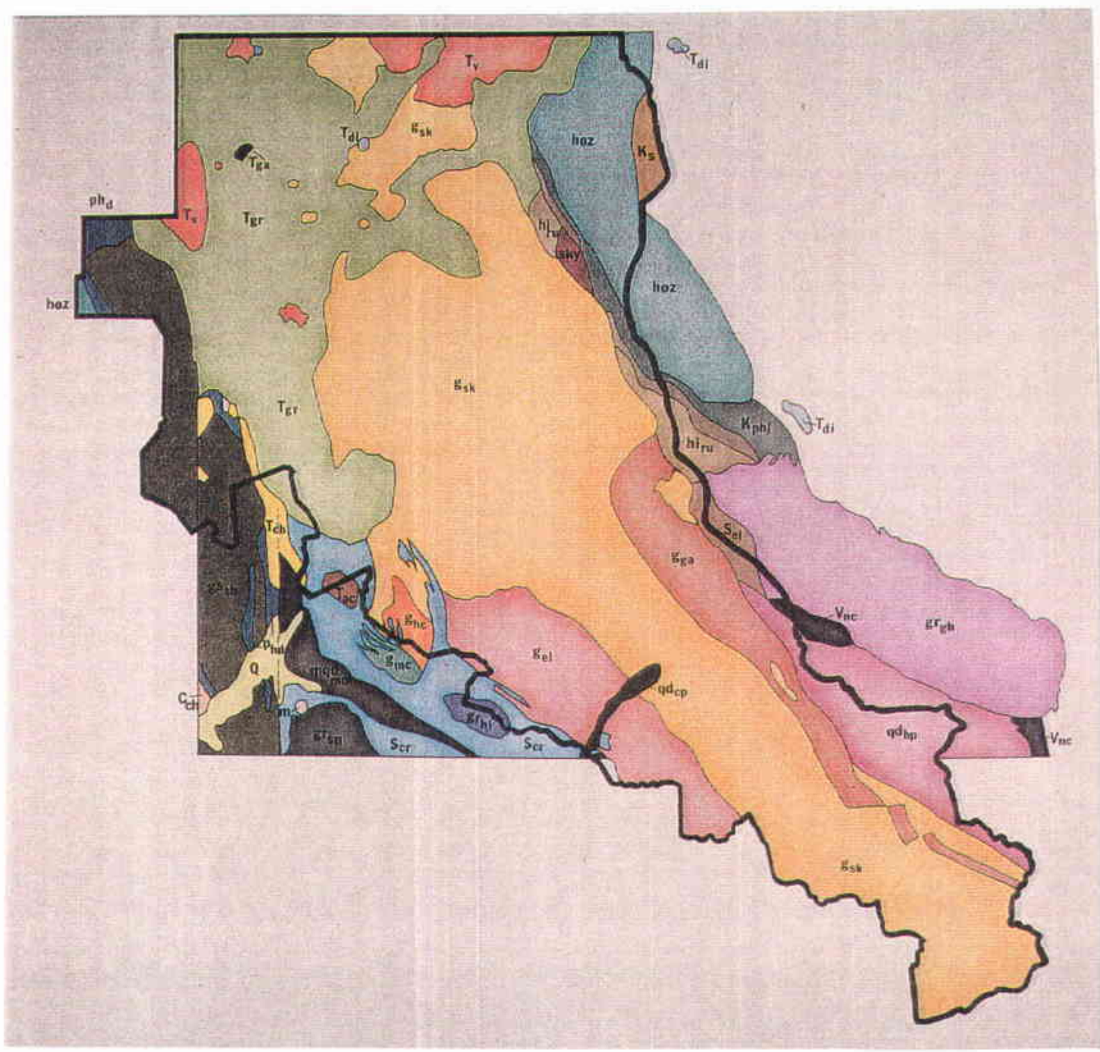


Figure 4. The geology of North Cascades National Park Service Complex. The exposed section of Straight Creek Fault is represented by the dotted line. A band of metamorphics (hi_{ru}, sky, K_{phj}), delineates the Ross Lake Fault zone. After Misch (1977), Staatz et al. (1972).

CENOZOIC STRATA:

- Q — Quaternary deposits
- Tv — Volcanics with associated clastics (Skagit Volcanics, Hannegan Volcanics)
- T_{ch} — Chuckanut Formation

NON-METAMORPHIC LATE CRETACEOUS AND CENOZOIC PLUTONIC ROCKS:

- qd_{cp} — Cascade Pass Quartz Diorite
- T_{gr} — Granitic rocks (quartz-dioritic to quartz-monzonitic) of Chilliwack Composite Batholith
- T_{di} — Diorite stock
- T_{ga} — Gabbro stock
- gr_{gh} — Golden Horn Batholith, alkaline granite to quartz monzonite
- gr_{sn} — Snowking Massif
- gr_{hl} — Hidden Lake Stock
- hi_{ru} — Ruby Creek Heterogeneous Plutonic Belt, gabbroic to granitic
- qd_{bp} — Black Peak Batholith, quartz diorite and grandiorite

W. OF STRAIGHT CREEK FAULT:

- C_{ch} — Chilliwack Group

SHUKSAN METAMORPHIC SUITE

- gs_{sh} — Shuksan Greenschist
- ph_{d} — Darrington Phyllite

SKAGIT CRYSTALLINE CORE:

SKAGIT METAMORPHIC SUITE *sensu stricto*

- S_{cr} — Cascade River Schist
- g_{sk} — Skagit Gneiss

GRANITE INTRUSIVES ASSOCIATED WITH CASCADE RIVER SCHIST

- t_{ac} — Alma Creek Leucotrondhjemite
- g_{hc} — Haystack Creek Leucotrondhjemitic Orthogneiss
- g_{mc} — Marble Creek Trondohjemitic Orthogneiss with quartz-dioritic and grandioritic varieties
- mp — Metaperidotite

MAJOR ORTHOGNEISS BELTS ASSOCIATED WITH SKAGIT SUITE

- g_{ga} — Gabriel Peak Orthogneiss
- g_{el} — Eldorado Orthogneiss
- mqd_{mm} — Marblemount Meta Quartz Diorite

E. OF ROSS LAKE FAULT:

- K_{s} — Sedimentary formations, undifferentiated
- K_{phj} — Jack Mountain Phyllite
- V_{nc} — North Creek Volcanics
- S_{el} — Elijah Ridge Schist
- hoz — Hozomeen Group
- sky — Skymo Creek Granulitic Complex

Figure 4. Geology legend.

deepened by glacial activity. This reinitiated the development of soils, removed vegetation or altered successional stages, and covered and enlarged most existing lake basins. The Cascade crest was breached by glaciers which captured the Skagit river and rerouted its flow into Puget Sound. Neoglaciation—or alpine glaciation—reworked most of the present-day land forms and existing lake basins at the higher elevations about 2500 years ago (Crandell 1965). Flowing from the headwalls, glaciers carved depressions and deposited moraines and other land forms of alluvium and outwash, some which have remained as morphogenetic features of lake basins. Today, remnant glaciers are reminders of a much more severe climatic regime from the past. These glaciers potentially influence some lake processes by providing inputs of turbid meltwater. The glacial meltwater cools lakes and provides increased levels of phosphorus compounds to the biological assemblages.

Climate

Differential precipitation across the hydrologic divide separates NOCA into two major climatic units (Jackson and Kimerling 1993, Porter 1976). Westslope, a maritime climate, provides warm, moist air coming off the Pacific Ocean and Puget Sound. This ensures wet and relatively warm winters, while summers remain cool. East of the crest, a more semi-arid, continental climate occurs. Because of a different potential capacity, this climate exhibits colder winters and relatively hotter, dryer summers compared to a maritime climate. Throughout the park, ice and snow blanket most watersheds and lakes approximately nine months each year. Rains during the brief summer are common, particularly westslope.

Vegetation

Westslope park vegetation is typified by lowland and montane forests. Lowland forests are generally below the permanent winter snowpack while montane forests exist in areas where snow remains the entire winter. The subalpine zone is composed of lush herbs and woody shrubs. Alpine vegetation is recognized by krumholtz, a growth form rather than any particular species. Rock and ice dominate the alpine zone. Eastslope forests, which are drier than westslope counterparts, generally have less understory. Eastslope subalpine and alpine vegetation is similar to westslope vegetation.

Watershed and Lake Morphology

The morphology of a watershed basin can influence wind fetch; drainage development; avalanche potential (relative to providing inputs of organic materials into lakes); lake depth, temperature, trophy, and rate of turnover; the date the lake is ice-free; and potentially many other characteristics (Figure 3). Within a lake, morphology can influence the extent of the littoral zone, substrate composition, temperature profile, and the concentrations of dissolved oxygen and other chemical compounds. Origin identifies features reflective of a lakes morphology, often its relative position in the watershed, and relative persistence.

METHODS FOR DETERMINING BIOPHYSICAL PARAMETERS NEEDED FOR CLASSIFICATION AND ITS APPLICATIONS

Physical

U.S. Department of the Interior, Geological Survey (GS) topographic maps (7.5') were used to determine lake watershed area, surface area, elevation, and presence or absence of permanent inlet streams for 162 NOCA lakes determined to be important to fisheries management by state and National Park Service biologists (Jarvis 1987). A BASIC program, GAP4 (GTCO 1982), was used to manually digitize the flat-map watershed area and surface area of each lake. Lake elevation was recorded from the Park Service database, and geology was determined from existing literature.

As part of field testing the classification, 58 lakes were surveyed from 1989–1992 using field crews that either flew to the sites in helicopters or hiked to the lakes. The surveyed lakes were selected on the basis of a preliminary classification developed by Lomnicky and others (1989). Bathymetric maps of each surveyed lake were created by taking transects using a hand-held, sonar, depth finder. Depth isopleths were interpolated, and volumes were determined using a digitizer, $V= h/3[A_1 + A_2 + \sqrt{(A_1A_2)}]$, where h = depth between frustrules and A_x = area of a frustrule. With this data, mean depth (MZ) was determined for each lake using $MZ = V/A_o$, where A_o = surface area. If only the maximum depth was known, lakes were assumed to be perfect cones and lake volume was determined using $V = h/3(\pi r^2)$. Temperature was measured over the deepest spot in the surveyed lakes at 1-m intervals from the surface to the bottom using an Omega HH70 series handheld thermometer with a single input, Type K, chromel-alumel thermocouple.

Date of ice-out—defined as the time at which the lake surface becomes virtually ice-free—was determined for most lakes from weekly aerial surveys over the park. For a few lakes not covered by the aerial surveys, I relied on information obtained in interviews with backcountry rangers.

Mean precipitation values for lake watersheds were taken from a map developed by Agee and Pickford (1985) that used state climatological data and added revisions based on local survey information.

Chemical

A total of 142 water samples were collected (1989–1992) from 58 lakes. Water samples were collected 1 m below the surface near the deepest spot in each lake from inflatable boats using a 1.5 l Van Dorn style bottle. Filtered (0.7μm prewashed Watman GF/C filters) nutrient and trace element samples were placed in 1-l acid-washed, high-density, polyethylene bottles. Unfiltered samples (250 ml acid-washed polypropylene bottles) were collected for determination of conductivity, alkalinity, and total phosphorus. To the degree possible, water samples were taken just before leaving the field site to minimize sample deterioration. If samples were kept overnight in the field, the bottles were placed out of the light to the degree possible or in dark bags and kept in the coldest spot that could be found (an inlet or outlet stream, an undercut bank in the lake, or in snow banks). When departing the field site, samples were wrapped with insulation to maintain coolness, transported out of the field, frozen, and then shipped to the laboratory. Chemical analyses (Table 2) including alkalinity (ALK), ammonia-N (NH_3), calcium (Ca), conductivity (COND), magnesium (Mg), nitrate (NO_3), orthophosphorus (OP), pH (PH), potassium (K), total Kjeldahl-N (TKN), total

Table 2. Analytical procedures used by the Cooperative Chemistry Analytical Laboratory, Oregon State University.

Variable (Acronym)	Method	Detection limits	(Units)
Conductivity (COND)	Wheatstone Bridge, Yellow Springs model 33, corrected to 25°C	0.4	(mS/cm)
Nitrate-N (NO_3)	Technicon Autoanalyzer,automated cadmium reduction	0.001	(mg/l)
Kjeldahl-N (TKN)	Nessler's Reagent finish	0.01	(mg/l)
Ammonia-N (NH_3)	Technicon Autoanalyzer, colormetric automated phenate	0.005	(mg/l)
Total Phosphorus (TP)	Persulfate digestion, ascorbic acid finish	0.001	(mg/l)
Orthophosphate-P (OP)	Reactive phosphate,ascorbic acid finish	0.001	(mg/l)
pH (PH)	Portable Beckman meter 21. Orion Sureflow Standarized with pH 4 and pH 7 buffers. Final reading recorded after 5 consecutive readings of the same value (usually 30-45 minutes)	0-14	
Alkalinity (ALK)	Electrometric titration to pH 4.5	0.2	(mg/l)
Sodium (Na)	Flame atomic absorption	0.01	(mg/l)
Magnesium (Mg)	Flame atomic absorption	0.001	(mg/l)
Calcium (Ca)	Flame atomic absorption	0.06	(mg/l)
Potassium (K)	Flame atomic absorption	0.03	(mg/l)

phosphorus (TP), and sodium (Na) were performed at the Cooperative Chemical Analytical Laboratory, Oregon State University.

Vegetation

In the absence of sufficient data on climate, soil maturity, and hydrologic regimen, vegetation was used as a proxy to provide indirect understanding of these factors for classification at the watershed level. Vegetation was considered a good integrator of these components because of the long time-frames needed for development and persistence of vegetative assemblages and associations (Aber and Melillo 1991, Franklin and others 1988).

A vegetation map (Agee and Pickford 1985), which was developed using LANDSAT multispectral scanner images and other data (slope, elevation, aspect) on a Geographic Information System (GIS), provided initial identification of cover types for the NOCA lake watersheds. Watersheds were identified as predominately alpine, subalpine, or forest based on the vegetation types and near-lake vegetation in the basin. The forest zone was further subdivided into high- and low-elevation subgroups based on location above (maintains winter snow cover till spring) or below (intermittent snow-free ground cover during the winter) permanent winter snowpack. This forest-zone determination was based on local vegetation known to be found associated with or without permanent snow.

Vegetation cover of unsurveyed and surveyed lakes was cross-checked with aerial photographs. Predominant plant-assemblage types and associations were assessed in the field as a final check to verify that each lake had been placed into the correct vegetation zone. Elevation ranges for each vegetation zone were determined from Agee and Pickford (1985) by identifying vegetation types for a particular zone and then recording the maximum and minimum mean ranges for the assemblage in each zone. The lakes were identified as westslope or eastslope based on their position relative to the hydrologic crest. Westslope lakes drain into Puget Sound (Washington) and the Fraser river (British Columbia) while eastslope lakes drain into the Columbia River (eastern Washington).

Phytoplankton

In 1989, 61 phytoplankton samples were collected throughout the park from late June through mid-September from 57 individual lakes as part of an initial survey to develop baseline data on a representative selection of park lakes. These lakes and their basins encompassed the range of NOCA vegetation zones (from low-elevation forest to alpine systems), surface areas, depths, origins, geographic locations (east and west, north and south) and developmental age (young, glacially turbid lakes to much more productive lakes in forest basins) of lakes located within the park.

Samples were collected using a Van-Dorn style water sampler from a depth of 1 m near the deepest portion of each lake. Each 1-l phytoplankton sample was preserved with 10 ml of 95% Lugol's Acetate (Lind 1974). The phytoplankton in each sample were identified and enumerated to the lowest taxonomic level possible by Robert Truitt (Research Assistant, Oregon State University Cooperative Park Studies Unit) using an inverted microscope (McIntire and others 1993). In nearly all cases, 500 cells were counted per sample to obtain relative densities of each observed taxon. Large amounts of debris from glacial out-wash in five of the samples only permitted counts of 100 cells. A multiplier was estimated for each taxon based on cell diameter and was used to transform counted data into estimates of cell biovolume.

Zooplankton

Vertical tows for zooplankton were taken from 53 lakes between 1989 and 1993. Lakes were sampled after lakes became ice-free (approximately mid-June to mid-July) and before the return of inclement fall weather (mid-September). Samples were collected with a 20-cm, diameter number 25 (64µm mesh), zooplankton net from near the deepest point in each lake. The net was lowered to within 1 m of the bottom of the lake, or to at least 10 m in deep lakes, and then retrieved to the surface at a rate of about 0.5 m/sec. Three replicate vertical tows were taken for all lakes except in 1989 when only one vertical tow was taken. Samples were preserved in the field with 5% neutral sugar formalin (Haney and Hall 1973) and split in the laboratory with a Folsom plankton splitter. Split samples were poured into a settling chamber and left to settle for 24 hr before processing could continue. Organisms were identified and enumerated by Elisabeth Deimling (Research Assistant, Oregon State University Department of Fisheries and Wildlife) and Robert Truitt (Research Assistant, Oregon State University, Cooperative Park Studies Unit) while using an inverted microscope at 100X magnification.

Fish

Fish (presence and absence) data for all lakes were determined from park files. Field verification and reassessment of population status were carried out for all lakes visited. Fish were collected by angling and with gillnets. Additional observational information was determined by walking inlet and outlet streams and by snorkeling lake shorelines. Based on fish presence or absence, the park database, and other information, lakes were assigned to one of three classes: no fish present (NF), fish present but no natural reproduction occurring (FNR), or fish present that are known to be reproducing (FR). The ability for fish to reproduce was based on spawning habitat availability and/or presence of multiple-year classes of fish that did not correspond to known stocking records.

Statistical Methods

Physical

The Kruskal Wallace/Mann Whitney-U nonparametric analysis of variance (SYSTAT, Wilkinson 1990) was utilized to test for statistically significant differences between lake classes. Statistical significance was set at $P = 0.05$. Level of significance for multiple comparisons with these same data was determined by using a Bonferroni adjustment (dividing the chosen significance level ($P = 0.05$) by the number of comparisons to arrive at a conservative *P* value) (Miller 1981).

Regression and covariance analyses (Wilkinson 1990) were used to elucidate the relation between epilimnion temperature and ice-out date and the variables vegetation class and elevation.

The diversity—by origin—of lakes within a selected vegetation zone was determined using the Shannon information measure (HE) within the AID1 program (Overton and others 1987):

$$HE = -\sum p_{ij} \log_e(p_{ij}),$$

where p_{ij} is the relativized datum for attribute i on sample unit j, ($p_{ij} = n_{ij}/N_j$) and n_i is the number of lakes of a given origin class in a sample of N lakes.

Chemistry

For many analyses, an overall mean of each chemical parameter for each lake, which was determined over all sampling occasions of that particular lake, was used to reduce the influence of any lake that had been sampled multiple times. A mean value for each chemical parameter for each lake was determined by averaging all samples collected for each lake from 1989 to 1992. For most analyses, overall average values were used to avoid skewing analyses with some lakes that were repeatedly sampled. Average pH was calculated from hydrogen ion activity.

Partial analysis of lake chemistry data was performed using CLUSB (McIntire 1973), a non-hierarchical divisive, clustering algorithm that created clusters of lakes based on a minimum variance partition of standardized data, the distance of each lake from the group centroid (a multidimensional mean) for the lakes. Sequential clusters were initiated by finding the lake most distant from the previous cluster. Each lake was then re-evaluated relative to the new centroid (outlier lake) versus the old centroid, and lakes were regrouped with the nearest cluster centroid. The process is iterative and additional clusters were created until, and as long, as the clusters made ecological sense. For this analysis, each sampling occasion was considered a separate lake in an effort to determine if seasonal variation would lead to separation of early season (June) samples from late season samples (September), or if lakes would remain in relatively close proximity in phase space both annually and seasonally. Discriminate and correlation analyses (SPSS statistical package) were used on the finalized cluster groups for graphical display and axis (ecological) interpretations.

Principal Components Analysis (Ludwig and Reynolds 1988) was performed on a limited subset of lakes sampled over multiple years to identify potential seasonal and annual variance in chemistry. The derived ordination axes scores for each lake were regressed against abiotic variables for axis interpretation.

Euclidean Distance was calculated, using the group averaging method, to aid interpretation of chemical differences in cluster groups. Distances were derived based on standardized physical and environmental variables (watershed vegetation zone, hydrologic crest position, lake elevation, mean depth, origin, average epilimnion temperature, bedrock type, conductivity/mean depth, watershed area/lake volume, aspect, ice-free date).

Fishers' Exact Test ($P = 0.05$, Siegal 1956) was used to compare individual lakes differing in maximum depth and near-surface and near-bottom temperatures. Lakes were placed into a two by two matrices (four groups), two by depth (≥ 10 m, < 10 m) and two by the difference in water temperature(≥ 5°C, < 5°C m) between near-surface (1 m) and near-bottom depths.

Phytoplankton

Phytoplankton was analyzed at two levels of taxonomic classification. The first was an analysis at the division level, except for Chrysophyta (class level), using data collected from 1988 through 1993. Acronyms were as follows: Chlorophyta (CHL), Chrysophyta (CHR), Bacillariophyta (BAC), Cyanophyta (CYN), Pyrrhophyta (PYR), Cryptophyta (CRY), Euglenophyta (EUG), and an unknown (UNK). The second was an analysis of the phytoplankton at the most specific taxonomic level (usually at the species level) and included only the data collected in 1989. Ordinations of the data at the division and species levels were performed using detrended correspondence analysis (Hill and Gauch, 1980) and canonical correspondence analysis (CANOCO, Ter Braak 1986). CANOCO creates ordination axes that are linear combinations of environmental variables, and it allows phytoplankton-assemblage information to be directly related to quantitative or nominal environmental information. Proportional abundances and biovolumes were calculated using the program AIDN (Overton and others 1987). A cluster analysis (McIntire 1973) was used to group the samples in ordination space for comparison with physical and chemical cluster-analyses. SYSTAT (Wilkinson 1990) was used for multiple regression tests and correlation analyses to ordination axes.

Zooplankton

Mean densities of adult crustacean zooplankton of each taxon for each lake sampling (sample means) were calculated from the three replicate vertical tows (except for the 1989 data when only one tow was collected). From this data, the proportional abundance of each taxon among all lakes was calculated. A single mean for each taxon in each lake was calculated by averaging data within each year (if the lake had been sampled many times), then averaging again over all years (if lakes had been sampled more than one year). Therefore, a single, overall, mean density was determined for each lake and used in subsequent analyses. Ordinations of the data were performed using CANOCO (Ter Brakk 1986) to graphically display relationships between means of vegetational classes based on zooplankton taxa.

Discriminate analysis

Lakes were first grouped by one of three " classification" systems (hierarchical lake classification, lakes grouped by crustacean zooplankton taxa (overall mean density per lake), and chemical groups (mean concentration per lake) derived from ClusB cluster analysis. These imposed classifications were then subjected to discriminant analysis (NCSS vers. 5.03, Hintze 1992) to determine the relative correspondence between the imposed classifications on the lakes and the predicted classes for the lakes based upon discriminant functions derived from the data for each classification group. The discriminant function derived for each class or group predicted which classification category each lake should be assigned based on shared similarities associated with the presence of taxa or chemistry variables within each class or group.

DELINEATION OF NOCA HIERARCHICAL CLASSIFICATION

Geology and Soils

Geology was not used as a primary classification variable since most lakes occurred on gneiss and granitic lithology, two very similar lithologies in terms of chemical compounds released to the lakes. However, differing lithologies provide dissimilar capacities for influencing weathering processes which affect basin shape, soil development, and, thus, vegetation colonization and succession processes..

Westslope watersheds were geologically more complex than eastslope watersheds. Gneiss was the predominate bedrock of eastslope watersheds, with only a few lakes found on granitic plutons. Westslope lithology was dominated by gneiss, granite, sedimentary, and volcanic deposits. Though local soil surveys are not completed, regional soils are primarily young cryandempts that formed during cool summers (Jackson and Kimerling 1993).

Classification Results

Level I. Position relative to hydrologic crest.

Climate was determined to be the overriding factor in making the first division of classes. All lakes were classified either as westslope or eastslope (Figure 1) based on their location relative to the hydrologic crest of the North Cascade mountains. Major patterns of air masses, which seasonally influenced air temperature, amount, and form of precipitation, aspect of major watersheds, and geology, differed with crest position. Lake watersheds on the westslope were associated with the Skagit, Chilliwack, or

Nooksack river systems. Eastslope watersheds drain into the Stehekin river, a tributary to the Columbia river.

Warm moist air rising from the Pacific Ocean and Puget Sound is transported in a northeasterly to easterly direction by winter seasonal air flow patterns (Figure 5). As the air rises up the western flank of the Cascades, precipitation increases (Figure 6). On the eastslope, rain-shadow effects decrease the average amount of precipitation available relative to amounts on the westslope (Figure 6). By comparison, summer wind patterns transport air masses from the northwest bringing precipitation to the westslope. Overall precipitation is greatest in the northwest portion of the park (Figure 6).

Snow is the predominant form of precipitation during the winter months, and glaciers have developed in areas of heaviest snowfall, particularly at the highest elevations on the north- and northeast-facing slopes of westslope basins. Glaciation, snow and rain all significantly affect individual lake basins because of their impacts on water quality from flushing by snowbelt and other runoff and turbid glacial inputs (Brundin 1958, Wetzel 1983, Hem 1989). Glacial influence was observed over the region and factored in to the classification at the first level only on a qualitative basis.

Annual temperature extremes are greater eastslope than on the westslope because of clearer skies on the eastslope (Jackson and Kimerling 1993). Westslope skies are often covered by clouds from marine moisture. This results in hotter summers and colder winters on the eastslope in comparison with the westslope (Jackson and Kimerling 1993).

Figure 5. Air mass movements over North Cascades National Park Service Complex. Winter flows originate from the southwest (indicated by large, light blue arrows), and summer flows (white arrow) originate from the northwest.

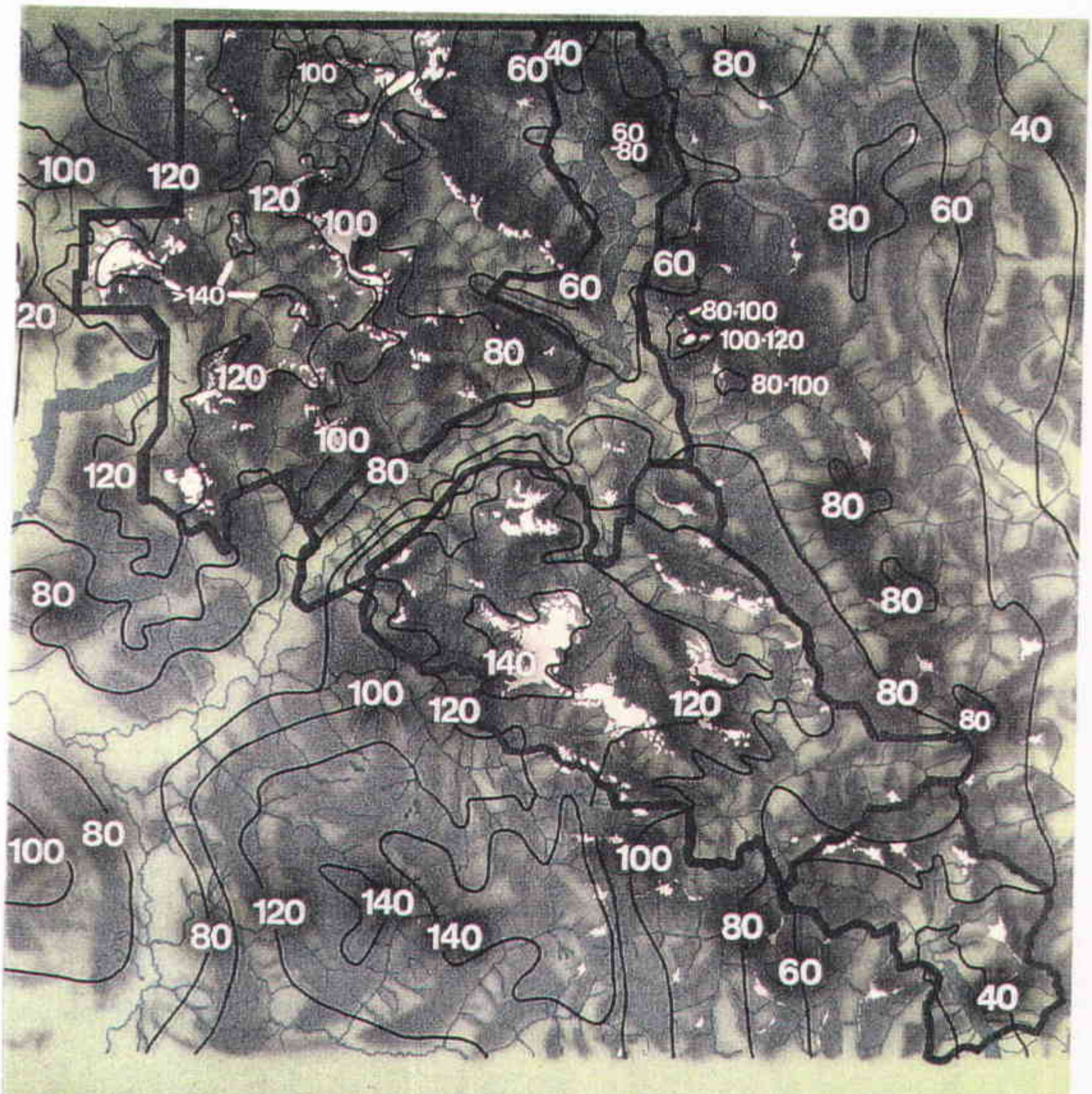


Figure 6. Annual precipitation pattern over North Cascades National Park Service Complex. Developed from state climatological maps and survey data collected by Agee and Pickford (1985).

Level II: Vegetation Zone

The second level of the classification was based on vegetation, and four vegetation zones (alpine, subalpine, high forest, low forest) were identified. The alpine zone is dominated by exposed rock and ice (Table 3). Dominant vegetation is clumped, low in stature, and includes sedges (*Carex* sp.), stonecrop (*Sedum* sp.), and partridgefoot (*Leutkia* sp.). The alpine zone occurs primarily in westslope watersheds where the climate is conducive to the persistence of glaciers and alpine conditions. Thirty-six lakes 28%of westslope lakes) were found to occur in this zone (Table 3). The semi-arid climate of eastslope watersheds generally was too dry and warm for glacial and alpine conditions to persist. Consequently, only 3 of the eastslope lakes (9%) were found to exist in this zone (Table 3).

The subalpine zone is intermediate to the alpine and forest zones (Table 3). Dominant vegetation includes herbs, woody shrubs, and some trees aggregated in open forests. Herbs include partridgefoot (*Leutkia sp.*), a variety of ferns and mosses, sedges (*Carex* sp.), and hellebores (*Veratrum* sp.). Common woody shrubs are heather (*Phyllodoce* sp.) and huckleberry (*Vaccinium* sp.). Westslope trees include mountain hemlock (*Tsuga mertensiana*), Pacific silver fir (*Abies amablis*), and subalpine fir (*Abies lasiocarpa*). Eastslope trees include mountain hemlock, occasional Alaska yellow cedar (*Chamaecyparis nootkatensis*), subalpine fir and, at the higher elevations in the zone, whitebark pine (*Pinus albicaulis)* and subalpine larch (*Larix lyalli*) (Table 3). Sixty-nine percent of the eastslope (24/35) and 53% (67) of the westslope lakes were identified as subalpine lakes.

The forest zone was subdivided into high-forest and low-forest zones according to presence or absence of a permanent winter snowpack on both the eastslope and westslope. High-forest zones experience permanent winter snowpack, whereas low-

Table 3. Vegetation zones for lake basins with corresponding cover types (Agee & Pickford 1985) and cover type mean elevations for open and closed forest, lake elevations (minimum & maximum), habitat notes and NOCA lakes. Sampled lakes in bold type. Lake acronyms given in Appendix I.

Vegetation Zones	Major Cover Types Found in Lake Basins	Mean Elevation Ranges for Vegetation zones(m) (Lake Elevations)	Habitat Notes	Lakes by origin[a,b]
EASTSLOPE				
Forest Low	Ponderosa pine, Douglas-fir	– 880 (662)	Very dry, low elevation. Douglas-fir to mid elevation. Disturbance oriented (fire, avalanche) communities.	**B-COON**
High	subalpine fir, mountain hemlock, subalpine herb, heather	1127–1789 (1504–1717)	Subalpine fir found in more xeric areas than mountain hemlock. Forests communities tend to be more xeric tolerant than westside counterparts.	**C-BATT MCAL** **T-DAGG, KETT, KETU, RAIN, WADD**
Subalpine	subalpine fir, whitebark pine/larch, subalpine herb, rock, snow	1558–2231 (1270–2072)	Mesic aspects east. Larch found at higher colder areas than pine. Summer warmth has allowed subalpine vegetation types to extend to the ridgetops in most basins.	**C-DOUB**, MA3, MLy1, MM7, MR1, **MR9, MR11, MR13-1**, MR15-1, MR15-2, **TRIL** **T-GNVW, TRAP** **I- JUAN**, ML6, **MM11, MR2, MR3**, MR8, MR12 D-MM1, **MR13-2, TRIU** B-MR16
Alpine	rock, snow	(1860 – 2127)	High elevation xeric environment. Limited summer season and permanent winter snowpack.	I- MA2, MM3 D-MM8
WESTSLOPE				
Forest Low	hardwood forests, high shrub, western hemlock, douglas-fir	488–880 (412–1031)	Warm low elevation, dry to moist areas generally below permanent winter snowpack. Marked by disturbance oriented communities and western hemlock. High shrub extends up avalanche slopes. Disturbance oriented species (douglas-fir) may be seral to silver fir.	**C-PYRA** **T-HOZO**[d], MP5, **PANL, PANU, RIDL**[d], **THUN, WILL**[d]
High	Pacific silver fir, douglas-fir	728–1316 (1171–1687)	> 100 inches/yr rainfall. Winter snowpack does not melt off periodically during winter	**C-BOUC, JEAN, LS1, LS2**, MC8, **NONA, THRL** **I- NERT**[d] **D-SWEE**[b] S-EP3 **K-PM5(1-6)**

Table 3, Continued.

Vegetation Zones	Major Cover Types Found in Lake Basins	Mean Elevation Ranges for Vegetation zones(m) (Lake Elevations)	Habitat Notes	Lakes by origin[ab]
Subalpine	Rock, snow, subalpine herb, subalpine fir, mountain hemlock, silver fir, heather	1220—1789 (1110–1967)	Basins tend to be meadow filled with clumps of trees if any. Often snow persists in basin throughout the summer.	C-**BEAR**, **COPP**, DD5, **EGG**, EP2, EP5-1, **EP6**, EP9-2, EP12, FP9, FP10, LS3, LS6, LS7[b], M11[b], M14, M17, MC3, MC7, MC16-2, MC29[b], MC34, **MONO**, MP2, MS3, MSH4, **TAP1**, **THRM** T-**HIDD**, M4[b], M8, MC14-1, MC14-2, **PRIC**[c], **REVL**, **SKYM**, **WILD** I- EP9-1, EP13, FP6, M24-1, M24-2, MC1 MC2, MC15, ML3, MP1(1-3), PM2, **TAP2**, TAP3, **TAP4** D-DD8, M21, MC28[c], ML1, PM12, **REDO**[b], **REVU**, **VULC**[b] B-M1, MC10, **TTAR**[d] F-M7 U-M15, MSH2
Alpine	Rock, snow, subalpine herb, subalpine fir	(1113 - 2083)	Severe, large quantities snow, rock and ice. Vegetation, if any, is of krummholtz form.	C-EP4, EP10, LS5, M10, M13, M18, M22, MC13, MC16-1, MC23, **MP8**, MP9, MS2, MSH1[c], OUZL[c] T-EP11-1,**KLAW**[c], **MORA**[c], SILV, SKYU I- **EILE**, EP14, FP5, LS4, MC22, **WILE** D-FP1, M9, M16, MA1[b], ML5 U-EP11-2, FP8, M25, MC30, RD4

[a]Origin: C = cirque, T = trough, I = ice scour, D = moraine dam, B = bench, F = fault, S = slump, K = Kettle, U = not defined
[b]Some glacial influence
[c]Turbid glacial inflow
[d]Sedimentary geology

forest zones do not. High-forest zones are dominated by silver fir on the westslope and by mountain hemlock and subalpine fir on the eastslope. Low-elevation forests include ponderosa pine (*Pinus ponderosa*) and douglas-fir (*Pseudotsuga menziesii*) on the eastslope, and douglas-fir and western hemlock (*Tsuga heterophylla*) on the westslope. Understory vegetation was found to be sparser on the eastslope than on the westslope. On the eastslope, seven high-forest lakes and one low-forest lake were identified. On the westslope, 6% (8/127) of the lakes were low-forest and 13% (16/127) were high-forest lakes.

Climatic differences between the eastslope and westslope influence the occurrence of the vegetation zones relative to elevation. All three eastslope vegetation zones occur at higher average elevations than their counterparts on the westslope (Table 3). The alpine zone is restricted on the eastslope, but occurred in a significant portion of westslope watersheds. Lakes in eastslope alpine watersheds are scarce, but alpine lakes are much more numerous in westslope alpine watersheds. Subalpine zones and high-forest zones predominate on both the eastslope and westslope. Lakes in the low-forest zones in NOCA were most common westslope and rare eastslope (Table 3).

Precipitation varied among vegetation zones. Average annual precipitation tended to decrease from the subalpine to the low-forest zone east and west of the hydrologic crest (Table 4). On the westslope, there was little difference in precipitation between alpine and subalpine zones, but the amount of precipitation decreased from the subalpine to the low forest zone. Average amounts of precipitation for each vegetation zone were lower for eastslope zones than for westslope zones (Table 4). The amount of precipitation in high-forest westslope watersheds was approximately equal to precipitation in alpine and subalpine watersheds on the eastslope.

Table 4. Elevations (EL), precipitation (PREC), and date of ice-out for NOCA lakes by position east or west of the Cascade crest and vegetation zone.

Vegetation zone	Statistics	EL (m)	PREC (cm)	ICE-OUT* (julian days)
a. Eastslope				
Alpine	mean	1961	237	NA†
	N	3	3	NA
	SD	145	29	NA
Subalpine	mean	1847	211	188
	N	24	24	11
	SD	177	52	20
Forest High	mean	1648	196	176
	N	7	7	5
	SD	1	32	20
	mean	662	152	95
Forest Low	*N*	1	1	1
	SD	-	-	-
b. Westslope				
Alpine	mean	1601	287	216
	N	36	36	8
	stan. dev.	250	56	16
Subalpine	mean	1566	290	205
	N	67	67	18
	stan. dev.	187	53	16
Forest High	mean	1360	232	182
	N	16	16	8
	SD	125	58	16
Forest Low	mean	810	187	138
	N	8	8	7
	SD	230	38	20
c. Parkwide	mean	1564	262	187
	N	162	162	55
	SD	300	64	31

*Surveyed lakes, 1989
†Not Available

Level III: Origin

Lake origins were determined by interpretation of black and white stereo-photographs of all park lakes. Origin types were identified and adapted from descriptions from Hutchinson (1957). A total of 152 lakes were identified by basin origin (Table 3). The origins of 10 lakes were left undetermined, and no field determinations were made for these lakes.

Eight lake classes, based on catchment origin, were identified including cirque, trough, ice scour, moraine, bench, fault, slump, and kettle lakes. Cirques are amphitheater shaped basins generally occurring at the heads of glaciated valleys, and thought to be formed by frost riving at the firn line (permanent snow line). Troughs are lakes formed in glacially scoured U-shaped valleys, and they tend to be long, narrow, and wedge-shaped with the deepest spot in the lake near the outlet. Ice-scour lakes, found in irregular depressions, were formed by glacial scour along fault or joint fracture lines and tend to occur on ridgetops. Moraine lakes formed behind the unconsolidated till of terminal or lateral moraines. This damming feature may have acted alone to form the lake or increased the depth of an existing cirque or trough lake. Bench lakes originate from glacial scouring either working at two different time periods to create a step or bench that is oblong in shape along a hillslope parallel to a valley floor or from long periods of nivation at that elevation. Bench lakes have no sheltering basin. Fault lakes occurred behind bedrock dams created by differential displacement of bedrock along tectonic faults. Slump lakes occur in the depression left by the rotational slip of deep-seated soil. Kettle lakes were the result of irregularly deposited outwash (ground/terminal moraine) or remnant pieces of ice left in the outwash of retreating glaciers, and these kettle lakes tended to have irregular shapes. When the ice melted, a lake was left in the resulting depression.

APPLICATIONS OF CLASSIFICATION: PHYSICAL, CHEMICAL AND BIOLOGICAL CORRELATES

Lake classification was used to assess some specific characteristics of NOCA lakes: distribution of the lakes by class relative to time of lake ice-out, epilimnetic water temperature, and water chemistry; the influence of lake depth on water temperature and chemistry; the influence of geology on water chemistry; and a measure of the integrated influence of watershed characteristics on lake nutrients. Finally, classification was used to interpret the parkwide distribution and structure of selected biological assemblages including phytoplankton, zooplankton, and fish.

Physical Variables

Basin Origin

Each morphogenetic class exhibited differences in depth, landscape position, presence of a permanent inlet stream, several other morphogenic features, relief of the watershed basin, and inferred differences in relative persistence because of initial differences in potential capacity. Though a wide range of depths were associated with basins created by erosional processes including troughs and cirques, maximum depths tended to be greater for these lake classes than for other lake types (Table 5). Lakes formed through depositional processes including slump lakes and kettle lakes—which were small, shallow depressions—may have shorter temporal persistence than the other lake classes because of ontological infilling processes that are occurring at generally faster rates. Moraine-dammed lakes tend to be hybrid lakes, containing a damming feature (e.g. ice-cored moraine) that potentially deepens an existing cirque or trough lake, and therefore may vary considerably in depth.

Table 5. Morphogenetic lake classes listed with general descriptors associated with each class. Temporal frame of reference and depth for North Cascades lakes (Maximum age to 7000 yr BP)

Lake class	Location	Relative Persistence	Relative depth* (m)	Permanent inlet stream	Basin relief	Morphogenetic feature
Cirque	headwall	long	shallow to deep (2–46.3)	generally no if headwall; yes if lower end of paternoster lakes	high	scoured depression at headwall with rock lip or moraine damming feature
Trough	valley	long	shallow to deep (3–137)	generally yes	low	glacially deepend valley depression with bedrock dam with occasional moraine influence
Ice Scour	ridgetop	long	shallow (1.2–8.2)	no	low	irregular depression created by glacial scour along fault or joint fracture
Moraine	valley,cirque	short to med	shallow to medium (4.3–27.4)	yes	variable	valley or cirque lake formed principally by terminal or lateral moraine dam
Bench	along valley side wall, a false ridge parallel to valley floor	medium to long	shallow to medium (3.6–5.8)	site specific	med to high	differencial valley glacier erosion along valley slope producing bench. Interaction with ancillary glacier
Fault	variable	variable	shallow to deep (11)	site specific	variable	tectonic displacement creating a bedrock dam with associated basin
Slump	on slope with deep soils, valley sidewall	short	shallow (no data)	no	medium	soil mass movement, rotational slip of deep seated soil
Kettle	ground moraine outwash	short	shallow (1–4)	no	low	stranded ice of retreating glacier leaves depression in ground moraine after melting

*Maximum depth relative to other classes of lakes by origin. Depths are for sampled lakes.

The location of each lake by origin was highly determining of several morphometric characteristics. For example, the presence of permanent inlet streams was related to lake position within a watershed. Permanent inlet streams influence thermal stratification (by mixing epilimnion and hypolimnion layers), dates of ice-out and ice-up (keeping water from freezing or providing mechanical action to break up ice), nutrient concentrations (flush the lake), and are potential spawning areas for trout. Low-elevation lakes in valleys, such as trough lakes, had the greatest occurrence of permanent inlet streams (Table 6). As expected, higher-elevation cirques and ice-scour lakes—which were situated up against headwalls or on ridges respectively where less drainage development had occurred—had relatively fewer inlet streams (cirques 32%, ice scour 10%). Twenty-eight percent of the dammed lakes, often hybrid trough or cirque lakes, had permanent streams. Slump (0%) and kettle (0%) lakes lacked permanent inlet streams, though sample sizes were small (1 and 6 respectively).

The percentage of permanent inlet streams for lakes differed between vegetation zones parkwide and eastslope versus westslope. The percentage increased across the park from alpine (18%) to subalpine (30%) to forest (45%) watersheds (Table 7).

Morphogenetic classes differed in watershed area, elevation, surface area, maximum depth and mean depth between vegetation zones and among each other (Table 8). These differences are due to differences in size, morphogenetic feature, and position within a watershed. Because of low sample sizes for some lake classes (bench, fault, slump, moraine dammed, and kettle), results are reported primarily for cirque, trough, and ice-scour lakes. Cirques increased in mean surface area from the

Table 6. Presence of permanent inlet streams for lakes identified by geomorphic origin for predominant geomorphic classes.

Origin	Parkwide Numbers	Percentage of lakes per origin
Cirque	20/63	30
Trough	16/27	60
Ice-scour	3/31	10
Moraine Dam	5/18	28

Table 7. Permanent inlet streams to lakes in North Cascades National Park indentified using U.S.G.S. 7.5' topographic and provisional topographic maps.
(N = 160)

Geographic region	Vegetation Zone	Presence/(total no.)	Percentage of each category
A. PARKWIDE			
	Alpine	7/40	18
	Subalpine	27/89	30
	Forest	14/31	45
B. EASTSLOPE			
	Alpine	0/3	0
	Subalpine	7/24	29
	Forest	6/8	75
C. WESTSLOPE			
	Alpine	7/37	19
	Subalpine	20/65	31
	Forest	8/23	25
		8/17*	47

* Without kettle lakes

Table 8. Minimum, maximum and mean values for NOCA lakes ordered by origin. N_{total}=152

		ALPINE					SUBALPINE					FOREST				
ORIGIN	STAT	WSHED (ha)	ELEV (m)	SA (ha)	ZMAX* (m)	MZ* (m)	WSHED (ha)	ELEV (m)	SA (ha)	ZMAX* (m)	MZ* (m)	WSHED (ha)	ELEV (m)	SA (ha)	ZMAX* (m)	MZ* (m)
CIRQUE	min	18	1159	0.4	3.7	1.5	6	1113	0.2	2.0	0.9	34	802	0.3	2.4	1.4
	max	806	1988	12.4	9.8	3.3	342	2072	35.6	46.3	16.2	449	1679	29.6	33.0	10.0
	mean	126	1603	3.2	6.8	2.4	72	1626	4.2	17.0	6.4	186	1318	7.2	10.0	4.0
	N		14		2	2		39		12	12		10		9	9
TROUGH	min	67	1211	1.1	4.3	1.7	17	1188	0.6	3.0	1.5	61	412	0.1	3.0	1.0
	max	1379	2063	65.1	137.0	45.7	644	1749	59.0	49.0	16.3	475	1717	38.4	19.0	6.3
	mean	736	1577	22.7	52.0	16.9	252	1534	17.8	23.3	8.5	238	1170	7.2	8.2	3.4
	N		5		4	4		12		6	6		10		9	9
ICE SCOUR	min	14	1479	0.7	4.6	1.3	1	1388	0.1	1.2	0.5	37	1388	1.0	8.2	2.9
	max	192	2127	2.4	4.6	1.3	62	2033	1.4	7.6	3.7	37	1388	1.0	8.2	2.9
	mean	54	1822	1.3	4.6	1.3	19	1793	0.5	3.6	1.7	37	1388 1	1.0	8.2	2.9
	N		8		1	1		22		6	6				1	1
MORAINE DAM	min	44	1113	0.5			39	1110	0.2	4.3	1.7	246	1687	3.4	27.4	13.0
	max	230	2083	7.1	ND	ND	392	1998	11.2	6.4	2.2	246	1687	3.4	27.4	13.0
	mean	124	1679	3.4			152	1549	2.5	5.2	1.9	246	1687 1	3.4	27.4	13.0
	N		6					11		3	3				1	1
BENCH	min						14	1159	0.4	3.6	2.0	40	662	8.2	5.8	2.7
	max	ND	ND	ND	ND	ND	85	1900	1.6	3.6	2.0	40	662	8.2	5.8	2.7
	mean						38	1562	0.8	3.6	2.0	40	662	8.2	5.8	2.7
	N							4		1	1		1		1	1
FAULT	min						556	1363	3.2	9.1	3.0					
	max	ND	ND	ND	ND	ND	556	1363	3.2	9.1	3.0	ND	ND	ND	ND	ND
	mean						556	1363	3.2	9.1	3.0					
	N							1		1	1					
SLUMP	min											131	1299	0.4		
	max	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	131	1299	0.4	ND	ND
	mean											131	1299 1	0.4		
	N															
KETTLE	min											11	1380	0.1		
	max	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	14	1397	0.2	ND	ND
	mean											12	1388 6	0.1		
	N															

* Surveyed lakes; mean depth determined for surveyed lakes having depth contour data.
WSHED = watershed (ha), ELEV = elevation (m), SA = surface area (ha), ZMAX = maximum depth, MZ = mean depth, ND = no data

alpine to the forest zone while trough and ice-scour lakes decreased. Trough lakes decreased in both maximum and mean depth from alpine to forest lake basins.

Trends were found among morphogenetic classes for watershed areas, elevations, surface area, maximum depth and mean depth (Table 9). For alpine and subalpine lakes, watershed area, surface area, maximum depth and mean depth tended to be greatest for trough and cirque lakes. In the forest zone, averages of the watershed and lake characteristics tended to be greater for cirques and troughs relative to ice-scour lakes.

Morphogenetic classes were unequally distributed across and within vegetation zones (Table 10). Trough, cirque, and ice-scour lakes occurred in all zones. The forest zone (high and low zones combined), which has the potential for the highest diversity of lake types due to ontological processes, contained the greatest diversity of morphogenetic classes (HE = 1.53 where HE = Shannon Information Measure), although this zone contained only 20% of all lakes. The alpine zone had the lowest diversity of morphogenetic classes (HE = 1.30) and contained lakes situated primarily in erosional land forms. Subalpine systems contained an intermediate diversity of morphogenetic classes (HE = 1.41), and the majority (58%) of the lakes in NOCA occur in this vegetation zone (Table 10). The occurrence of particular morphogenetic classes differed among vegetation zones (Table 10). The proportion of trough lakes increased from alpine to forest zones (15% in alpine, 13% in subalpine, and 33% in forest). Ice-scour and dammed lakes decreased in occurrence from alpine to forest zones. Cirque lakes were a major component of all zones, and as previously mentioned, slump and kettle lakes were present only in the forest zones.

Table 9. General trends of selected morphogenetic lake classes ordered by vegetation zone.

Watershed/Lake characteristic	Alpine Zone	Subalpine Zone	Forest Zone
WSHED	T > C > D > I	T > C > D > I	T > C > D > I
ELEV	I > D > C > T	I > C > D > T	D > I > C > T
SA	T > D > C > I	T > C > D > I	B > T = C > I
ZMAX	T > C > I	T > C > D > I	D > C > T = I
MZ	T > C > I	T > C > I	D > C > T > I

WSHED = watershed area; ELEV = elevation; SA = surface area; ZMAX = maximum depth, MZ = mean depth; T = trough; C = cirque; D = dam influenced lake; I = ice-scour lake; B = bench lake.

Table 10. Distribution of morphogenetic classes of NOCA lakes by vegetation zone.

ORIGIN	(*N*)	ALPINE (n)	SUBALPINE (n)	FOREST (n)
ICE-SCOUR	(31)	24% (8)	25% (22)	3% (1)
CIRQUE	(63)	42% (14)	44% (39)	32% (10)
TROUGH	(27)	15% (5)	13% (11)	33% (11)
DAMMED	(18)	18% (6)	13% (11)	3% (1)
BENCH	(5)	NA	4% (4)	3% (1)
FAULT	(1)	NA	1% (1)	NA
SLUMP	(1)	NA	NA	3% (1)
KETTLE	(6)	NA	NA	19% (6)
Totals % (N)	(152)	22% (33)	58% (88)	20% (31)

Relief frequency is the ratio between the highest elevation in the basin and the lake level divided by the distance between the two. Few significant differences (P_{α} = 0.05) in relief frequency were found between vegetation zones and eastslope versus westslope (Table 11). The relief frequency of forest westslope watersheds was significantly lower than subalpine watersheds. Differences in relief frequency between forest westslope and eastslope watersheds and between subalpine (combined) and forest (combined) were nearly significant. Forest westslope watersheds tended to have lower relief frequencies over forest eastslope watersheds and subalpine watersheds, and tended to have higher relief frequencies than forest watersheds. Relief frequency for alpine watersheds was more variable, resulting from the near proximity to ridges for many lakes, and not significantly different from subalpine and forest watersheds.

The drainage density of third-order streams did not differ relative to crest position and geology (Table 12). Eastslope and westslope watersheds averaged 1.07 kilometers of stream per square kilometer of area. Average stream density did not differ significantly between gneiss (eastslope vs westslope, Mann-Whitney U, P = 0.487). Different lithologies could only be compared westslope because the only eastslope third-order watersheds found entirely within one lithology were on gneiss. Though the average drainage density of streams in granitic watersheds (1.31 km / km^2) was higher than those of gneiss (0.99 km / km^2) or greenstone (1.09 km / km^2), no significant differences were found between granite and gneiss watersheds (P = 0.505).

Table 11. Relief frequency [(highest elevation in watershed - lake elevation) / (distance between highest point and lakeshore)] by vegetation zone and eastslope/westslope for lake watersheds within NOCA. (N = 132)

Vegetation Zone	*N*	Mean	Variance	95% CI
Alpine	23	45.3	274	38.1 < X < 52.5
Subalpine				
Eastslope	19	51.2	166	44.9 < X < 57.4
Westslope	59	44.5	204	40.1 < X < 47.6
Combined	78	45.6	203	42.4 < X < 48.8
Forest				
Eastslope	7	42.6	90	39.8 < X < 55.7
Westslope	23	34.5	149	29.2 < X < 39.8
Combined	31	37.9	165	33.2 < X < 42.7

Table 12. Drainage density for third-order streams that differed by crest position and by bedrock geology.

Watersheds (n)	Mean stream length per watershed (km)	Mean drainage area per watershed (km^2)	Average stream density per watershed (km/km^2)
Eastslope			
4	12.85	12	1.07
Westslope			
9	7.36	6.88	1.07
Granite			
2	7.30	5.56	1.31
Gneiss			
6	6.52	6.55	0.99
Greenstone			
1	12.50	11.5	1.09

Time of Ice-Out

Based on an analysis of data for eastslope and westslope lakes, differences in time of ice-out were found between vegetation zones, by crest position, and by basin aspect. Time of lake ice-out—measured in Julian days where January 1 was 1 and December 31 was 365—increased from low-forest lakes to alpine lakes (Table 4). Eastslope lakes were typically ice-free earlier than westslope lakes in each vegetation zone (Table 4). Ice-free date was also influenced by basin aspect. For a given elevation, lakes in west facing basins became ice-free sooner than lakes in east facing basins, when other criteria (lake size, depth, elevation) were relatively equal (Figure 7). For example, eastslope subalpine lakes with west-facing basins tended to become ice-free earlier than lakes with an easterly aspect (Figure 7a) even though elevations of the west facing lakes were higher. Westslope subalpine lakes tended to become ice-free at later dates with increasing elevation (except for EP6, TTAR, BEAR) but showed a less well-defined relationship with basin aspect than subalpine eastslope lakes (Figure 7b). EP6 and Bear are relatively larger, deep cirque lakes. Mixing of the water column resulting from wind induced movement of the ice, from convective density currents flowing along the sides of these lakes due to the release of stored heat from the sediments and solar radiation through windswept ice, or shear flow from inlet derived meltwater may allow these lakes to iceout slightly earlier than other west facing lakes of similar elevation. Skymo (SKYM) and Vulcan (VULC) were outliers. Perhaps Skymo, which like Talus Tarn (TTAR) is found in a rocky open basin, has greater late-winter subsurface flows resulting from melt water pouring into the lake from the upper basin (Upper Skymo lake). This inflow may allow the lake to become ice-free earlier than otherwise similar lakes or earlier than lakes in more sheltered locations. Vulcan

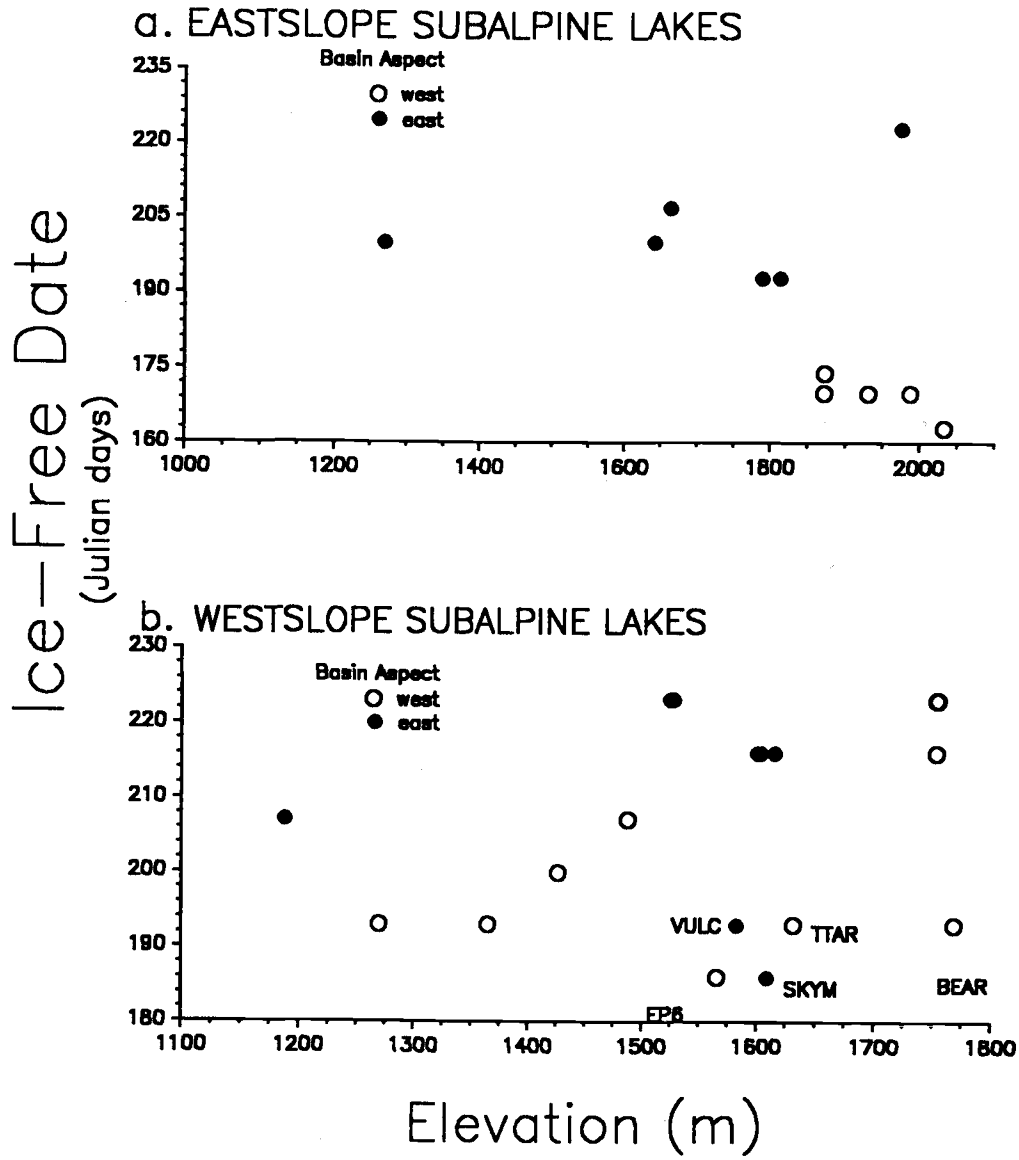


Figure 7. Relations between the estimated date of ice-out (Julian days), elevation (m), and basin aspect for eastslope and westslope subalpine lakes in 1989.

(VULC) varies from the pattern as well, becoming ice-free earlier than other westslope subalpine lakes with east facing aspects of similar elevation, and it may be influenced by groundwater entering the lake through the lateral moraine.

Epilimnetic Water Temperature

The water temperature within the epilimnion of lakes was warmest in low-forest lakes and coolest in alpine lakes based on measurements during the ice-free season in 1989 (Figure 8). The water temperatures of subalpine and high-forest lakes were very similar, and intermediate to the temperature of alpine and low-forest lakes. Furthermore, the water temperature of low-forest lakes was warmest in July, whereas the water temperature of high-forest, subalpine, and alpine lakes was warmest in September. Similar patterns were observed in 1990, even though a hot, dry August elevated water temperatures of subalpine, high-forest, and low-forest lakes by approximately 4°C relative to August 1989 (data not shown). Regressions of water temperature against elevation for lakes in the forest (high and low combined) and alpine zones revealed significant differences between these vegetation classes (Figure 9, ANCOVA, $P = 0.002$). Within elevation zones where alpine- and forest-zone class lakes overlapped, alpine lakes were approximately 5°C cooler for a specific elevation. This comparison suggests that local climate differed between lakes within these two zones, a result of differing potential capacities for climate. Thus temperatures were different though elevation was similar.

Differences in water temperature were also observed among lakes within each vegetation zone. For example, water temperature varied inversely with elevation within forest and alpine vegetation zones based on an analysis of 1989 data (Figure 9: Forest, $r^2 = 0.45$, $P = 0.002$; Alpine $r^2 = 0.51$, $P = 0.046$), potentially reflecting ambient

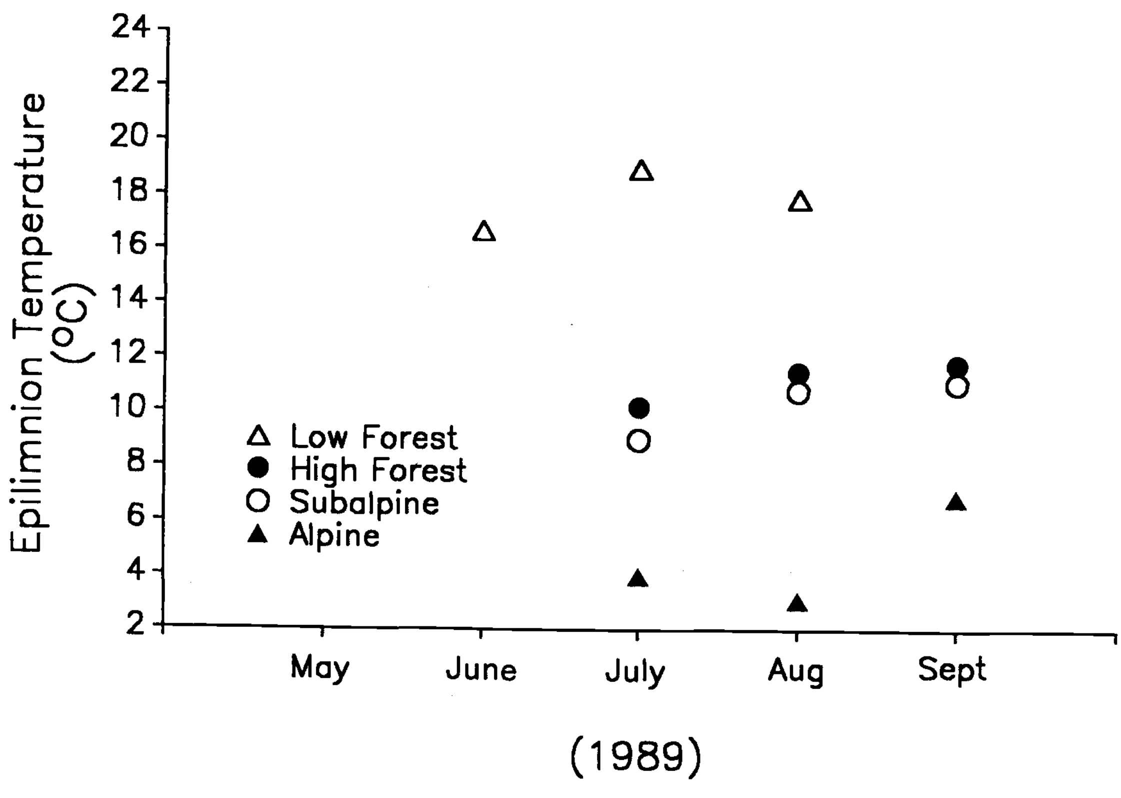


Figure 8. Relationship between epilimnion temperature (°C) and month for westslope vegetation zones. Each symbol represents the average temperature of all lakes sampled in a particular vegetation zone each month.

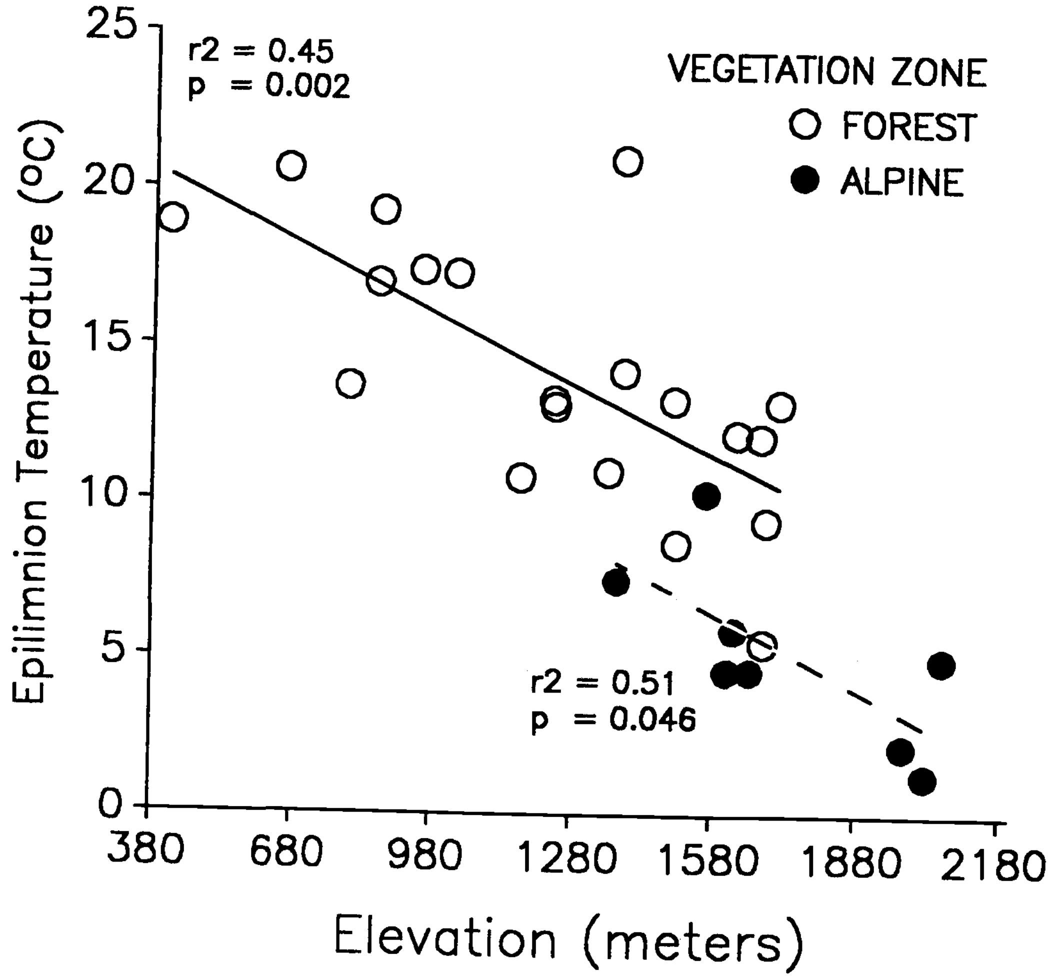


Figure 9. Relations between westslope mean epilimnion temperature (°C) and elevation (m) for forest zones and alpine zones.

air temperatures and the temperature of stream inflows, though some of the variation in water temperature within each lake class could be explained by lake depth. The difference between lake-water temperature measured at a depth of 1 m and temperature measured near the lake bottom was significantly greater for lakes ≥10 m in depth than for lakes < 10 m deep (Table 13). These results were obtained in comparisons using only measurements taken in August of 1989 ($P = 0.003$) when differences were expected to be maximized as well as with average measurements for the entire field season in 1989 ($P = 0.045$).

Lake Chemistry

Classification of lakes by crest position and vegetation zones did not clearly order the lakes relative to chemical characteristics. With the exception of westslope low-forest lakes, there were few significant differences in concentrations of total Kjeldahl-N, total phosphorus, orthophosphorus, nitrate-N, ammonia, pH, alkalinity, conductivity, and concentration of cations (sodium, potassium, calcium, and magnesium) between eastslope and westslope lakes regardless of vegetation zone (Table 14).

Westslope low-forest lakes differed significantly (Kruskal-Wallis, $P < 0.008$) from all other westslope vegetation zones in pH, alkalinity, conductivity, cations and total Kjeldahl-N (except high forest). Although there were few significant differences among westslope vegetation zones, pH, alkalinity, conductivity, and concentrations of total Kjeldahl-N, potassium, calcium, and magnesium tended to decrease from westslope low-forest to alpine lakes, and concentration of nitrate-N tended to increase, with nitrate concentration significantly greater in alpine than low forest concentrations (Kruskall-Wallis, $P < 0.008$). Total phosphorus was highest in concentration in alpine

Table 13. Fisher Exact probability test for significance between lakes ≥10 m deep and 5°C temperature difference between the bottom and 1-m depths for 1989.

	Depth	*N*	< 5°C	≥ 5°C	*P* value
Entire season	< 10 m	37	35	2	*P* = 0.045
	≥ 10 m	21	16	52	
August	< 10 m	5	4	1	*P* = 0.003
	≥ 10 m	10	6	4	

Table 14. Means and standard deviations (in parenthesis) for water chemistry variables 1989-1992.

	Eastslope			Westslope			
Variable	LF	HF	SA*	LF	HF	SA	ALP
N	1	5	12	7	9	16	8
TKN (mg/l)	0.147 (0.000)	0.064 (0.061)	0.055 (0.037)	0.112 (0.052)	0.045 (0.026)	0.024 (0.018)	0.018 (0.016)
TP (mg/l)	0.011 (0.000)	0.007 (0.003)	0.009 (0.006)	0.010 (0.003)	0.005 (0.003)	0.005 (0.005)	0.010 (0.009)
OP (mg/l)	0.002 (0.000)	0.001 (0.000)	0.001 (0.000)	0.001 (0.000)	0.001 (0.001)	0.001 (0.001)	0.002 (0.002)
NO3 (mg/l)	0.000 (0.000)	0.003 (0.002)	0.007 (0.009)	0.001 (0.000)	0.005 (0.006)	0.008 (0.008)	0.013 (0.011)
NH3 (mg/l)	0.004 (0.000)	0.005 (0.001)	0.005 (0.002)	0.008 (0.004)	0.006 (0.004)	0.006 (0.005)	0.003 (0.003)
PH	7.2	7.3	7.0	7.9	7.2	6.7	6.7
ALK (mg/l)	2.262 (0.000)	2.699 (1.680)	1.840 (1.164)	9.678 (5.597)	2.451 (1.75)	1.007 (0.878)	0.915 (0.479)
COND (μS/cm)	21.04 (0.00)	22.06 (14.30)	16.37 (12.37)	82.82 (41.85)	22.05 (16.67)	14.90 (18.77)	7.55 (4.39)
Na (mg/l)	0.620 (0.000)	0.488 (0.181)	0.425 (0.227)	1.160 (0.267)	0.368 (0.211)	0.274 (0.103)	0.189 (0.083)
K (mg/l)	0.270 (0.000)	0.194 (0.115)	0.155 (0.091)	0.434 (0.223)	0.155 (0.129)	0.114 (0.092)	0.159 (0.120)
Ca (mg/l)	3.530 (0.000)	3.266 (2.494)	2.239 (1.879)	12.643 (7.661)	3.214 (2.766)	1.502 (1.505)	0.864 (0.724)
Mg (mg/l)	0.521 (0.000)	0.282 (0.174)	0.236 (0.194)	1.330 (0.791)	0.350 (0.346)	0.142 (0.185)	0.107 (0.097)

*The three alpine lakes were not sampled.
LF = low forest; HF = high forest; SA = subalpine; ALP= alpine.

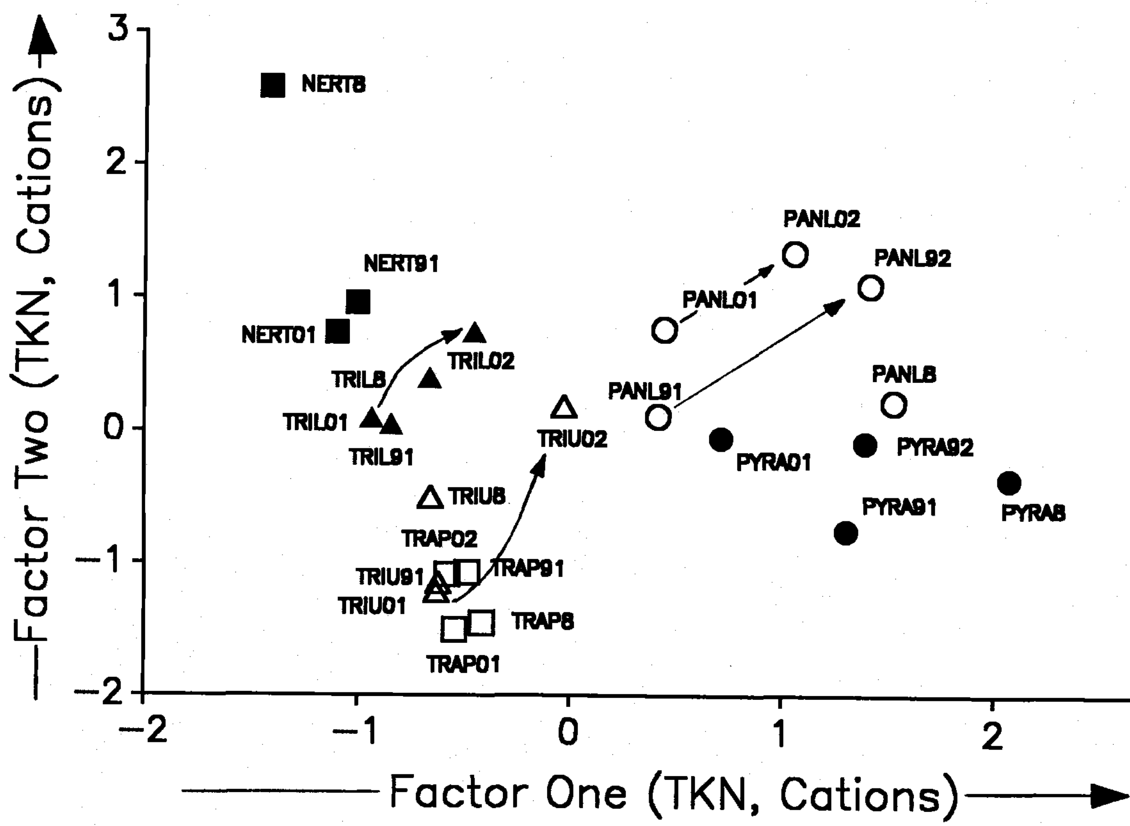
and low forest lakes. Westslope low forest differed significantly (Kruskall-Wallis, $P <$ 0.008) from eastslope subalpine lakes in pH, conductivity, alkalinity, and cations (except Mg). Other significant differences between eastslope and westslope lakes were few (total phosphorus, eastslope subalpine > westslope subalpine; Na, eastslope high forest > westslope alpine, westslope low forest > eastslope high forest).

NOCA lakes exhibited relatively little seasonal and annual variation in their chemical characteristics. Selected lakes sampled over three years remained in about the same region of phase space of a PCA ordination (Figure 10) from year to year and seasonally, though concentrations of cations and total Kjeldahl-N tended to increase from early season to late season (Figure 10a) for most lakes, and phosphorus increased (Figure 10b) for Upper Triplet (TRIU) and Lower Triplet (TRIL). Seasonal variation for lakes was not consistent.

Based on a cluster analysis of all samples (142) collected from 1989 to 1992, similar results were obtained; little seasonal and annual variation in chemical characteristics were found. For this analysis, each sample was considered unique to identify whether samples taken early or late in the season, or in different years, from the same lake would cluster together or separate out into different clusters. If variation of chemical parameters was high, samples would segregate. Based on ecological knowledge of the lakes and their watersheds, a five-cluster structure was selected. Lakes with multiple sample occurrences generally did not segregate into separate clusters by year or by season. Only two lakes with multiple samples were grouped in a second cluster by the algorithm. For analysis, these lakes were placed in the cluster containing all but the single anomalous sample for each lake.

The clusters were composed of lakes from glacially influenced alpine watersheds to low elevation, heavily forested basins, and could generally be ordered

Figure 10. PCA ordination of the water chemistry variables by lake for selected lakes showing annual and seasonal variation. a) Factor one versus Factor two. b) Factor one versus Factor three. Four digit lake acronyms (Appendix 1) are followed by a 5th digit marking year (8 = 1988, 9 = 1989, 0 = 1990), and 6th digit denotes the sampling occassion (1 or 2) within a given season. Each lake was identified with a unique symbol for clarity in graphical interpretation.



Factor Two (TKN, Cations)
Factor One (TKN, Cations)
3
2
1
0
−1
−2
−2
−1
0
1
2
3
NERT8
NERT91
NERT01
TRIL02
TRIL8
TRIL01
TRIL91
TRIU02
TRIU8
TRAP02
TRIU91
TRAP91
TRIU01
TRAP8
TRAP01
PANL02
PANL92
PANL01
PANL91
PANL8
PYRA01
PYRA92
PYRA91
PYRA8

Figure 10a.

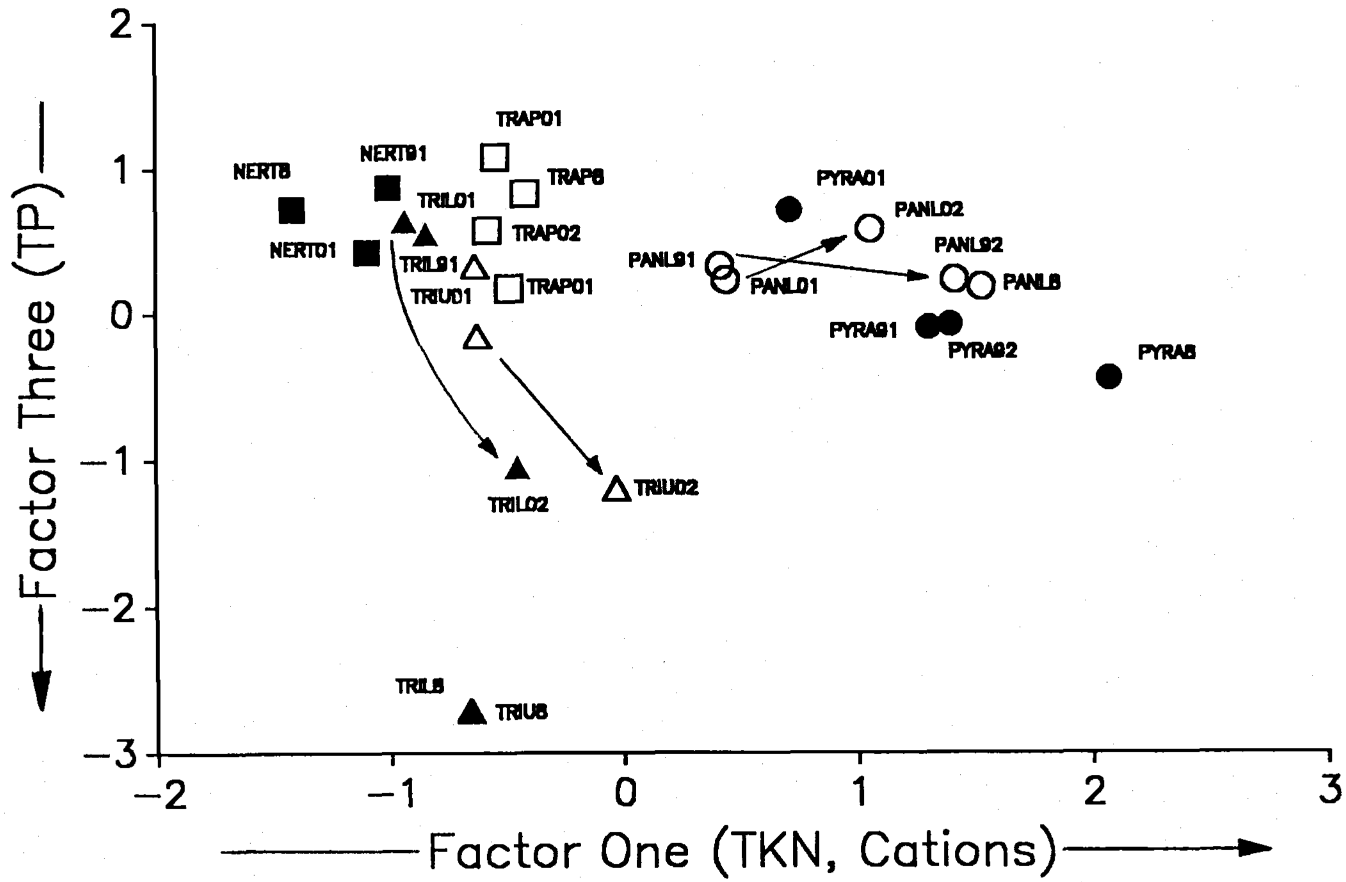

2
1
0
−1
−2
−3
−2
−1
0
1
2
3
Factor Three (TP)
Factor One (TKN, Cations)
NERT8
NERT91
NERT01
TRAP01
TRAP8
TRAP02
TRAP01
TRIL01
TRIL91
TRIU01
TRIL02
TRIU02
TRIL8
TRIU8
PYRA01
PANL02
PANL92
PANL91
PANL01
PANL8
PYRA91
PYRA92
PYRA8

Figure 10b.

along this continuum (Table 15). Cluster 5 was dominated by turbid alpine (67%, 2 of 3) and subalpine(33%, 1 of 3) lakes receiving glacial outwash. Subalpine lakes (63%, 20 of 32) dominated cluster 1, while subalpine (44%, 8 of 18) and high-forest (39%, 7 of 18) lakes dominated cluster 4. Clusters 2 and 3 contained only low-forest lakes.

A discriminate analysis was performed on the clusters to graphically determine their relative similarity in ordination space (Figure 11). Axis one was correlated with alkalinity (r^2=0.903), pH (r^2=0.760), conductivity (r^2=0.894), total Kjeldahl-N (r^2=0.437), Ca (r^2=0.948), Na (r^2=0.903), K (r^2=0.790), and Mg (r^2=0.363). Axis two correlated weakly with potassium (r^2 = 0.482). Axis three was correlated negatively with total phosphorus (r^2 = -0.632) and orthophosphorus (r^2 = -0.882). Thus, westslope low-forest clusters (2 and 3) were distinguished from other clusters (1,4, and 5) along axis one by tending to have higher alkalinity, pH, conductivity, total Kjeldahl-N, and cations (Table 16). Cluster 5—alpine and subalpine glacially influenced lakes—was distinguished along axis three by having higher levels of phosphorus than other clusters (Table 16). Clusters 1 and 4 contained the majority of the lakes (32 and 18, respectively). The lakes in cluster 4 tended to be lower in elevation, higher in total Kjeldahl-N, total phosphorus, pH, alkalinity, conductivity, and cations than the lakes in cluster 1(Table 16). Moraine lake (MORA), a glacially turbid alpine lake, seemed to be an outlier in cluster 4, though low elevation and high phosphorus contributed significantly to its placement.

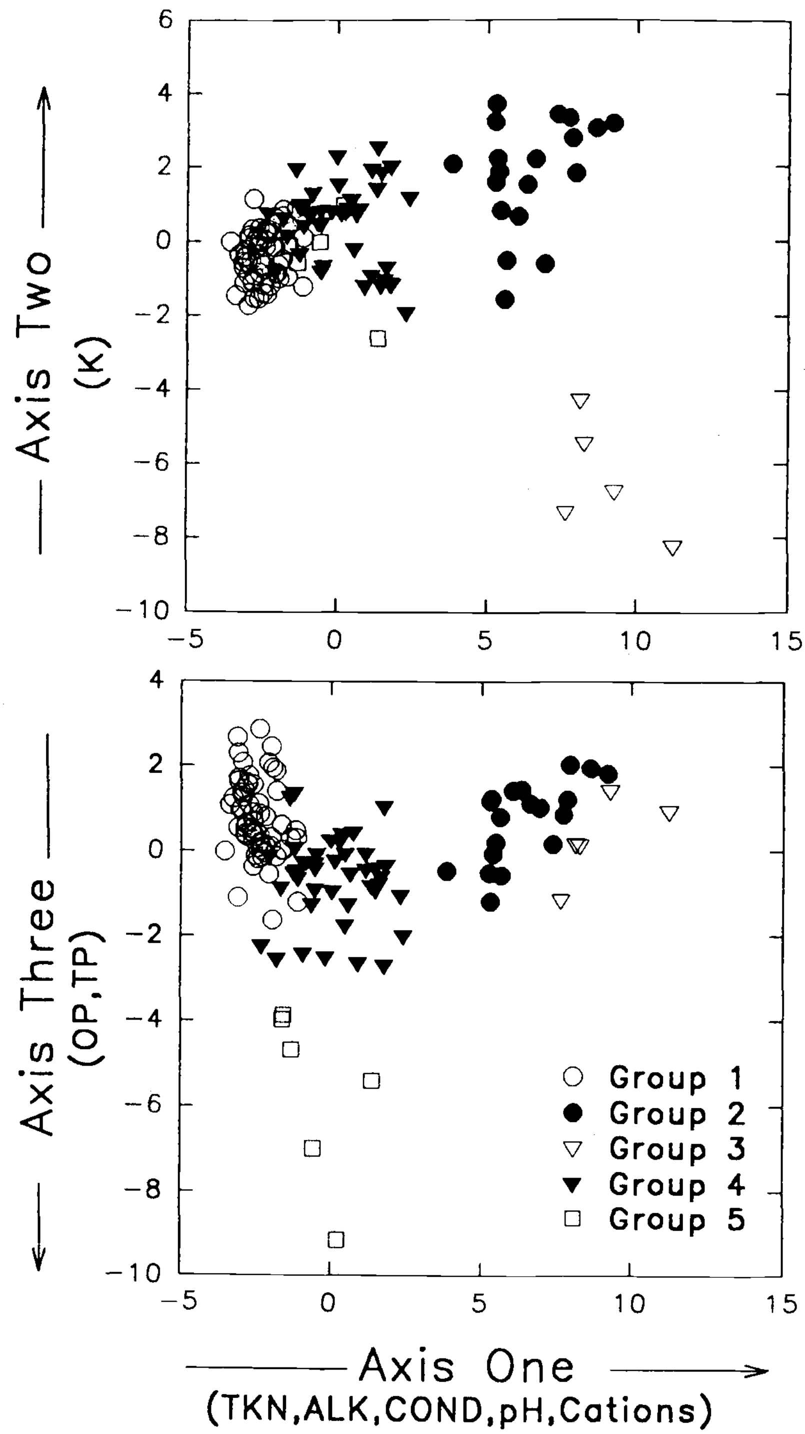
Clusters 2 and 3, both containing westslope low-forest lakes, were differentiated by geology. Cluster 2 contained lakes found in gneiss, a metamorphosed crystalline bedrock. Lakes in cluster 3 (HOZO, RIDL, and WILL) had the highest alkalinity, conductivity, and pH, and highest concentrations of TKN, Mg, and Ca in the park (Table 16). These lakes occurred in greenstone, a metamorphosed interbedded

Table 15. Summary of lake groupings developed using cluster analysis, based on water chemistry variables, 1989–1992. Each lake sample was considered an individual point. Two lakes with multiple samples had a single sample in a second cluster. Lakes occurring in more than one cluster were placed in the cluster containing the majority of samples for that lake. The clusters are organized from predominately alpine glacially influenced lakes to a cluster composed entirely of westslope low forest lakes. Lake acronyms are given in Appendix I.

			Vegetation Zone (percent)			
Cluster	*N**	Lakes	A	S	FH	FL
5						
Westslope	3		67	33	0	0
ALP		KLAW,OUZE				
SA		PRIC†				
1						
Westslope	32		16	63	21	0
HF		BOUC,LS1,NONA,PM53,THRL				
SA		BEAR,COPP,EGG,EP6,LS3, MONO,REVL,SKYM,TAP1, TAP2,TAP4,THRM,WILD				
ALP		EILE,MP8,SILV,SKYU,WILE				
Eastslope						
HF		RAIN,WADD				
SA		DOUB,GNVW,MM11,MR3 MR11,M131,M132				
4						
Westslope	18		6	44	39	11
LF		PANU				
HF		JEAN,LS2,NERT,SWEE				
SA		SKYM,TTAR,VULC				
ALP		MORA				
Eastslope						
LF		COON				
HF		BATT,DAGG,MCAL				
SA		JUAN,MR2,TRAP,TRIL,TRIU				
2						
Westslope	3		0	0	0	100
LF		PANL,PYRA,THUN				
3						
Westslope	3		0	0	0	100
LF		HOZO,RIDL,WILL				

*N represents the number of different lakes in each group
†Essentially alpine, resulting from heavy glacial influence

Figure 11. Ordination of lakes sampled from 1989–1992 relative to water chemistry variables. Groups defined by cluster analysis (Table 15) are shown. Discriminant analysis was used to graphically represent the clusters in ordination space. Arrows indicate increasing values of water chemistry variables. A total of 142 samples represent 58 lakes.



Axis Two
(K)
Axis Three
(OP,TP)
Axis One
(TKN,ALK,COND,pH,Cations)
Group 1
Group 2
Group 3
Group 4
Group 5
6
4
2
0
-2
-4
-6
-8
-10
-5
0
5
10
15

Figure 11.

Table 16. Cluster group means of selected water chemistry variables, 1989–1992.

Cluster	*N*	EL (m)	TKN (mg/l)	TP (mg/l)	OP (mg/l)	NH_3 (mg/l)	pH	ALK (mg/l)	COND (µS/cm)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)
5	6	1490	0.036	0.016	0.005	0.006	7.0	2.01	17.4	0.270	0.188	2.097	0.154
1	69	1621	0.033	0.005	0.001	0.005	6.7	1.15	10.6	0.272	0.097	1.243	0.124
4	43	1540	0.078	0.009	0.001	0.005	7.5	3.41	30.4	0.613	0.246	4.481	0.439
2	19	748	0.075	0.008	0.001	0.008	7.8	7.17	65.0	1.450	0.643	9.271	1.498
3	5	896	0.119	0.011	0.001	0.007	8.1	13.25	112.5	0.990	0.272	18.42	1.686

TKN : total Kjeldahl-N, TP : total phosphorus, OP : orthophosphorus, NH3-N : ammonia
ALK : alkalinity, COND : conductivity, Na : sodium, K : potassium, Ca : calcium, Mg : magnesium

sedimentary and volcanic bedrock , and tended to have lower concentrations of potassium than cluster 2 lakes.

Though variability in chemistry among and between the lake classes was high, trends were apparent from the cluster analysis that could be attributed to vegetation zone and physical variables. Chemical clusters were compared using Euclidian distance (ED)—a similarity measure— following the group-averaging method. Vegetation zone and physical data (hydrologic crest position, lake elevation, mean depth, origin, average epilimnion temperature, bedrock type, conductivity/mean depth, watershed area/lake volume, basin aspect, and ice-out date), which were determined for each lake of each chemical cluster, were used to determine correspondence between physical, vegetation, and chemical differences among chemical clusters. Relationships between vegetation zone and physical parameters of the clusters mirrored chemical relationships between the clusters derived from chemistry thus providing further support that the physical and biological environment is influential in determining lake chemistry. Chemical clusters 1 and 4 (ED = 1.86) and clusters 5 and 1 (ED = 1.93) and clusters 2 and 3 (ED 2.40) were most similar to each other (Table 17). Clusters 5 and 4 were intermediate in similarity (ED = 3.39), and clusters 5 and 3 were most dissimilar (ED=5.95) to each other. Lakes in cluster 4, had lower average elevations, were shallower, warmer, had a greater ratio of conductivity/mean depth, a more westerly aspect and iced-out earlier on average than cluster 1 lakes (Table 18). Cluster 5 lakes were similar to cluster 1 lakes except for the heavy glacial influence. Clusters 2 and 3, the low-forest lakes were similar (ED = 2.40) but differed from other clusters (Table 18) in elevation, epilimnion temperature, and ice-out. As with chemistry, clusters 5 (predominantly alpine lakes) and 3 (low-forest lakes) were most dissimilar

Table 17. Matrix of similarity values (Euclidean Distance) comparing vegetation zone and physical parameters (hydrologic crest position, lake elevation, mean depth, origin, average epilimnion temperature[1], geology, conductivity/mean depth, watershed area/lake volume, aspect, ice-out date[1]) for groups of lakes determined using cluster analysis. The groups of lakes were based on selected water chemistry parameters.

	1	2	3	4
2	4.69			
3	5.04	2.40		
4	1.86	3.59	3.80	
5	1.93	5.81	5.95	3.39

[1]1989.

Table 18. Mean values for physical parameters for each chemical group developed from CLUSB. Clusters are organized from the cluster with the most alpine lakes to the cluster with the most productive low forest lakes. (SD)

	Chemical Cluster				
Variable	5	1	4	2	3
Vegetation zone[1]	1.3 (0.6)	2.1 (0.6)	2.6 (0.8)	4.0 (0.0)	4.0 (0.0)
Eastslope/ Westslope[2]	2.0 (0.0)	1.7 (0.5)	1.47 (0.5)	2.0 (0.0)	2.0 (0.0)
Elevation (m)	1490 (262)	1621 (243)	1540 (356)	896 (54)	748 (313)
Mean Depth (m)	8.3 (4.4)	6.3 (8.4)	3.9 4.6)	4.2 (2.3)	3.47 (1.16)
Epilimnion Temperature[3] (°C)	5.1 (0.7)	10.4 (4.2)	12.9 (4.0)	17.8 (1.3)	16.7 (2.7)
Geology[4]	2.7 (2.1)	1.7 (1.0)	1.8 (1.3)	3.0 (0.0)	1.0 (0.0)
Conductivity/Mean Depth[5]	1.2 (0.4)	4.0 (5.8)	15.0 (10.5)	36.6 (21.6)	19.9 (5.4)
Watershed Area/ Lake Volume (ha/m^3)	2.43 (3.61)	2.48 (3.86)	6.77 (15.3)	0.85 (0.92)	5.43 (5.4)
Aspect[6]	1.33 (0.58)	1.37 (0.49)	1.65 (0.49)	2.0 (0.0)	2.0 (0.0)
Ice-out (Julian days)	210 (12)	201 (20)	175 (30)	146 (170)	131 (27)

[1]1 : Alpine; 2 : Subalpine; 3 : High Forest; 4 : Low Forest
[2]Relative to the hydrologic crest
[3]1989 season
[4]1 : Granite; 2 : Gneiss; 3 : Greenstone; 4 : Schist
[5]A proxy for the Morphoedaphic Index (Ryder 1965)
[6]Lake basin aspect; 1 : East; 2 : West

(ED = 5.95) both physically (elevation, mean depth, epilimnion temperature, geology, conductivity/mean depth) and environmentally (ice-out).

Specific factors that influenced water chemistry were lake depth and 'potential' flushing rate. Concentrations of total Kjeldahl-N and total phosphorus in lakes tended to decrease both eastslope and westslope as lakes increased in depth (Figure 12). The highest concentrations of total Kjeldahl-N and total phosphorus occurred in shallow lakes (< ~10 m), with the exception of three glacially influenced lakes (KLAW, PRIC, OUZL), total Kjeldahl-N and total phosphorus concentration were low in deep lakes. Schindler's ratio $[(A_o + A_d)/V]$, where A_o = watershed area, A_d = lake surface area, and V = lake volume, indicates the potential flushing ratio for each lake (Schindler 1971) and has been considered a general productivity index (Busch and Sly 1992). Concentration of total Kjeldahl-N appeared to increase and then decrease with an increase in Schindler's ratio for each vegetation class (Figure 13). Hand-drawn curves suggested that for a given ratio, total Kjeldahl-N decreased from low forest to alpine zones. Similar results were found for total Kjeldahl-N eastslope and for alkalinity and conductivity parkwide, but not for total phosphorus (data not shown).

In NOCA lakes, geology appears to play a minor role in segregating lakes based on their water chemistry. The water chemistry of lake basins in granite or gneiss did not differ significantly from one another. Only the low-forest lakes in greenstone were found to differ by having less potassium relative to the other low forest lakes found in gneiss (Kruskall-Wallis, $P = 0.008$).

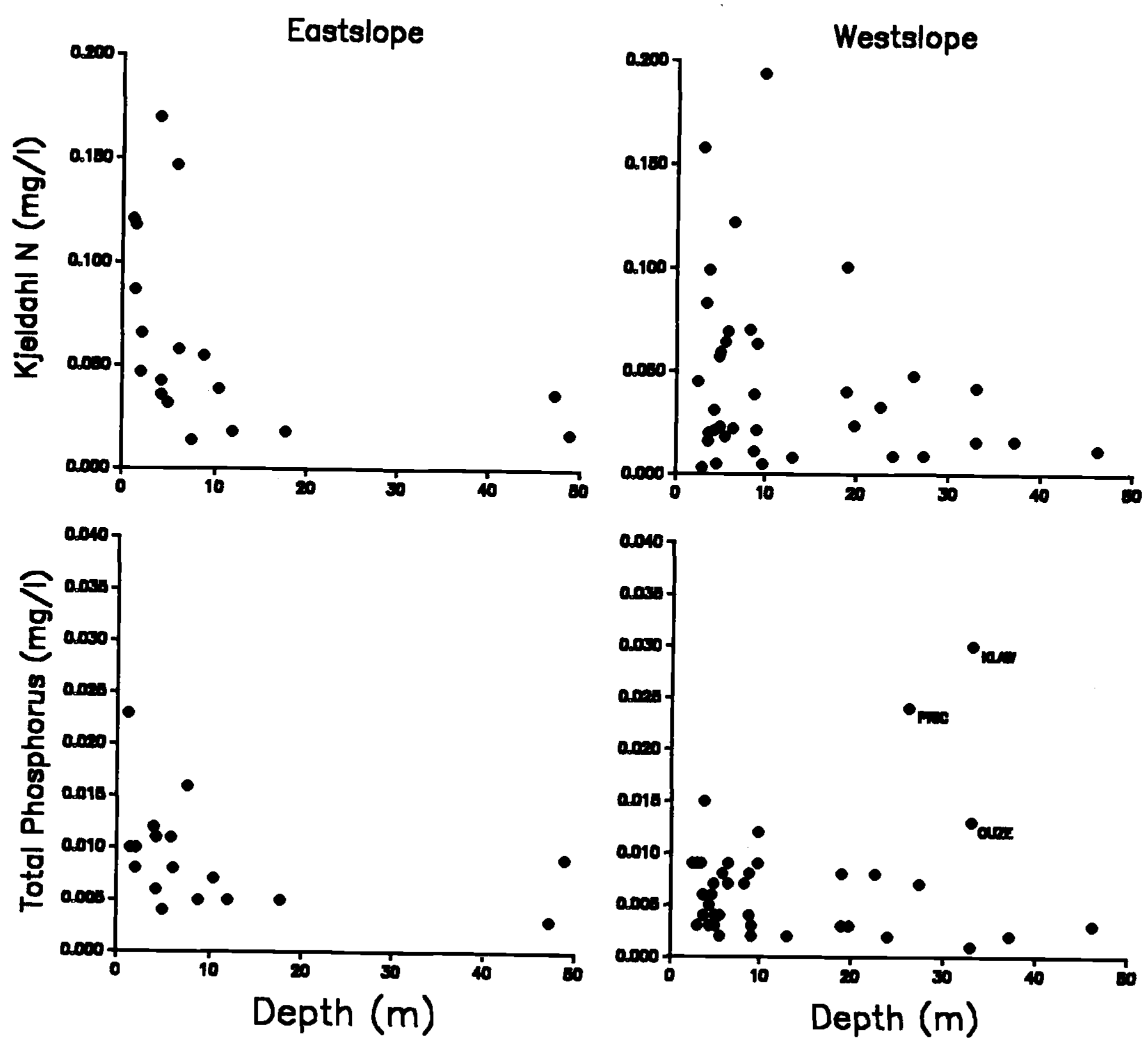


Figure 12. Relationship between total Kjeldahl-N (mg/l), total phosphorus (mg/l) and maximum lake depth for eastslope and westslope lakes.

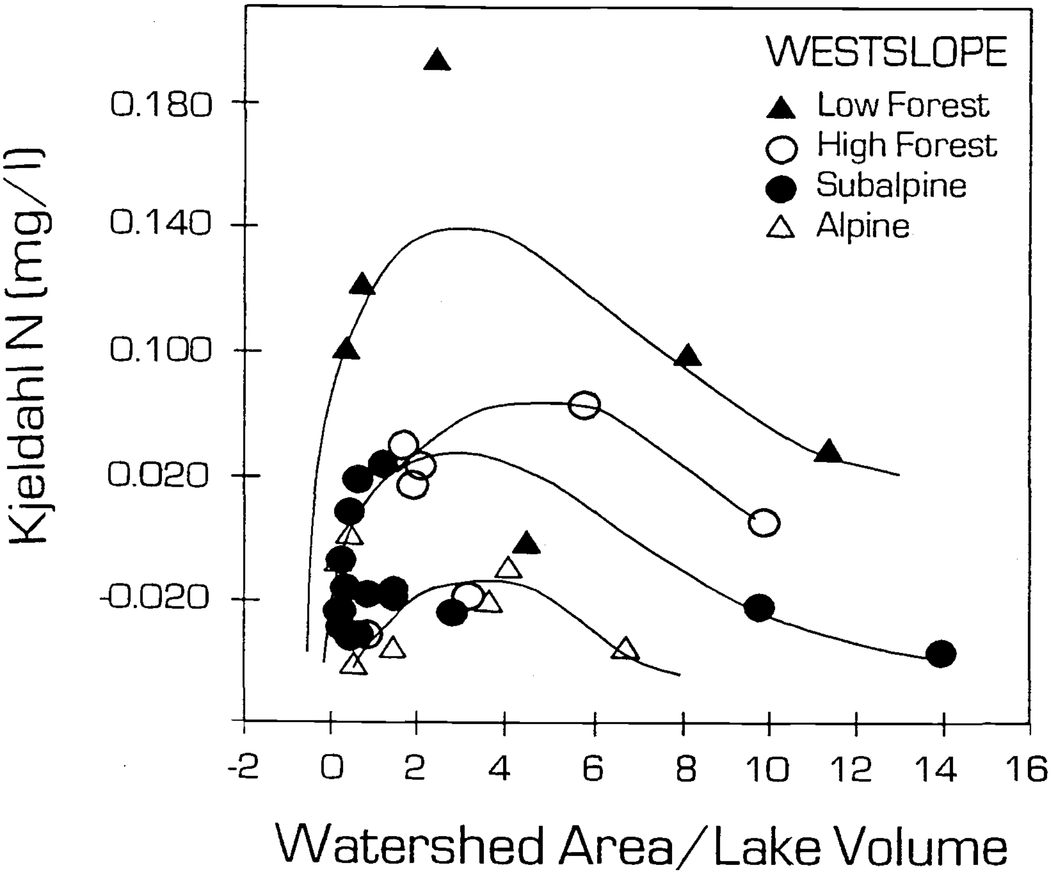


Figure 13. Relationship between total Kjeldahl-N (mg/l) and an index of flushing ratio (watershed area/lake volume) for westslope vegetation zones.

Biological Results

Fish

Trout are not indigenous to the high lakes of NOCA though they are distributed throughout the park because of stocking efforts this past century. The primary species stocked within the park are cutthroat (*Oncorhynchus clarki*) and rainbow (*Oncorhynchus mykiss*) trout. Though fish densities, presence and age distributions result from stocking rather than natural processes, some ecological patterns are evident and classification by vegetation zones provided insight to stocking strategies.

Lakes with fish tended to be deeper and have larger surface areas relative to lakes without fish (Table 19). Eastslope lakes with fish averaged 10.7 m in depth and 6.5 ha in surface area. Lakes without fish averaged 4.9 m in depth and 1.7 ha. Westslope lakes with fish averaged 16.1 m in depth and 8.3 ha. Both eastslope and westslope, lakes with reproducing populations of fish tended to be deeper and larger than lakes with non-reproducing fish (Table 19). Overall, for each category, westslope lakes with fish were deeper and had greater surface area than eastslope lakes.

Zooplankton

Discriminate analysis was used to determine the usefulness of zooplankton taxa for predicting lakes to classes previously based on terrestrial characteristics including climate and watershed vegetation. Zooplankton taxa associated with each of the four major vegetation zones found in the park (alpine, subalpine, high forest, low forest) were used to develop a classification equation for each vegetation zone. A classification matrix was constructed which was derived from the equations. Based on the taxa associated with each lake, lakes were assigned by the prediction equation to

Table 19. Fish presence in lakes at North Cascades National Park by crest position and by vegetation zone.

a. Crest position

	Eastslope			Westslope		
	Number	Lake maximum depth	Lake surface area	Number	Lake maximum depth	Lake surface area
No fish	17	4.9	1.7	85	3.1	3.5
Fish	18	10.7	6.5	41	16.1	8.3
NR*	8	10.4	2.9	19	13.5	5.5
Repro†	10	10.9	9.5	22	18.3	10.7

b. by vegetation zone

	Number		Percentage with fish
	Fish	No Fish	
Eastslope			
Forest	6	1	86
Low	1	0	100
High	5	1	83
Subalpine	12	13	48
Alpine	0	3	0
	18	17	51
Westslope			
Forest	12	9	57
Low	6	2	75
High	6	7	46
Subalpine	27	42	39
Alpine	3	33	8
	42	84	33

*NR = no reproduction

†Repro = naturally reproducing fish

the class which each was most likely to be a member. A particular lake was either assigned or not assigned to the appropriate vegetation-zone class 79% of the time (42 of 53) for all lakes. Prediction correspondence ranged from 54% (7 of 13) for high forest lakes to 100% (1 of 1) for alpine lakes. Prediction scores were 90% (28 of 31) for subalpine lakes and 75% (6 of 8) for low forest lakes. All six high forest lakes (DAGG, KETL, LS2, NERT, PM53, THRL) and the two low forest lakes (Hozomeen and Thunder) that were misclassified—were predicted to belong to the subalpine vegetation zone.

Taxa composition within lakes classified by crest position and vegetation class was highly variable, providing little discrimination between classes. Overall, only 15% of the lakes classified by vegetation class and crest position were successfully predicted to belong to their appropriate class. Two of the classes, eastslope alpine and low forest, contained single representative lakes, a violation of the assumption of having greater numbers of lakes than predictor variables. This appears to have negatively affected the discriminate analysis predictive functions for all classes based on crest position and vegetation zone. Additionally, it may suggest minimal eastslope/westslope effects, (i.e. that in the mountains, all subalpine lakes tend to be very similar, regardless of their position relative to the crest). Based on an analysis by Liss and others (1995) in which zooplankton assemblages in NOCA lakes were aggregated into eight clusters, eastslope/westslope physical and climatic differences do not appear to be dominate factors in discriminating lakes.

The clusters of lakes determined by water chemistry also were found to have utility in organizing zooplankton assemblages. Zooplankton taxa associated with each of the water chemistry groups (1-4) were used to develop a classification equation for each water chemistry cluster. A classification matrix was constructed which was derived from the equations. Discriminant functions derived for each group of lakes based on water chemistry predicted 77% (40 of 52) of the lakes to belong to the chemical cluster in which each lake had previously been assigned. Most lakes placed in cluster 1(ultra-oligotrophic, lowest TP), and all lakes placed in cluster 3 (low forest, highest alkalinity, conductivity, pH, TKN, Mg and Ca) by cluster analysis were predicted to belong in these cluster's by discriminant analysis (cluster 1,91%, 30 of 33; cluster 3, 100%, 3 of 3) . Only 38% (5 of 13) of the cluster 4 (oligotrophic, relatively moderate TP) lakes were correctly placed. All eight of the misclassified cluster 4 lakes were predicted to belong with the cluster 1 lakes. This result supports earlier analysis which identified the similarity of the water chemistry between clusters 1 and 4.

Centroids representing the group of lakes for each vegetation zone were distributed in ordination space relative to the distribution of zooplankton taxa to graphically display environmental relationships between lakes based on zooplankton assemblages (Figure 14). Coon lake was omitted from the analyses due to a single species found only in that lake, which made the lake an outlier in ordination analyses. Increasing scores of individual lakes along axis one corresponded to increasing concentrations ($r^2 > 0.500$) of total Kjeldahl-N, pH, alkalinity, conductivity, Na, K, Ca, Mg, ($r^2 > 0.500$ for TKN, pH, ALK, COND, and cations) and were negatively correlated with elevation ($r^2 = -0.628$) and ice-free date ($r^2 = -0.731$). Increasing scores on axis two weakly corresponded to decreasing total phosphorus concentrations ($r^2 = -0.345$). Eastslope subalpine lakes, which had relatively higher concentrations of phosphorus, were separated along axis two. Vegetation zones on both the eastslope and westslope were ordered left to right, from higher elevation alpine and subalpine lakes to the lower elevation forested basin lakes (EALP→WSA→ ESA→ WHF→ ESA→ WHF→ EHF→→ WLF). Westslope low forest lakes, which were located on the far right of the figure,

Figure 14. Ordination of lakes by vegetation zone based on proportional abundance of crustacean zooplankton species in each lake. Acronyms (Table 20) for taxa associated with each vegetation zone are shown. Centroids for each vegetation zone are shown. WLF = westslope low-forest; WHF = westslope high-forest; WSA = westslope subalpine; EALP = eastslope alpine; ESA = eastslope subalpine; EHF = eastslope high-forest.

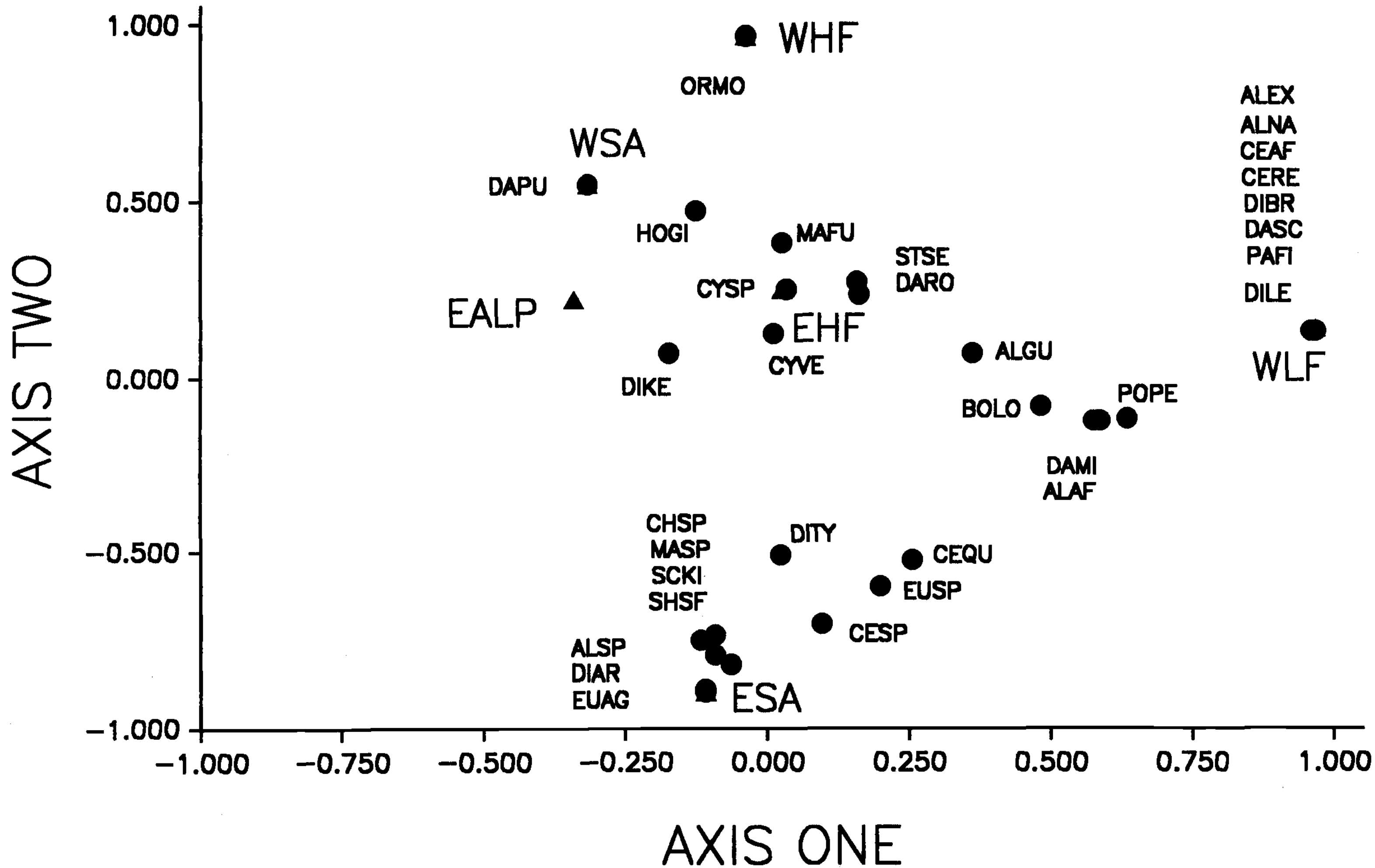

WHF
ORMO
WSA
DAPU
HOGI
MAFU
STSE
DARO
CYSP
EALP
EHF
DIKE
CYVE
ALGU
ALEX
ALNA
CEAF
CERE
DIBR
DASC
PAFI
DILE
WLF
POPE
BOLO
DAMI
ALAF
CHSP
MASP
SCKI
SHSF
DITY
CEQU
EUSP
CESP
ALSP
DIAR
EUAG
ESA
1.000
0.500
0.000
−0.500
−1.000
−1.000
−0.750
−0.500
−0.250
0.000
0.250
0.500
0.750
1.000
AXIS TWO
AXIS ONE

Figure 14.

were the most distinct class. A number of taxa (ALEX, ALNA, CEAF, CERE, DIBR, DASC, PAFI, DILE; Table 20) were only associated with these westslope low forest lakes. Taxa including *Diaptomus kenai* and *Daphnia rosea*, which are found near the center of the graph, were ubiquitous and thus present in lakes of many different classes.

Lake depth corresponded to the organization of the zooplankton assemblages. Lakes were identified as shallow ($Z < 8$ m) or deep ($Z \geq 8$ m) based on Liss and others (1995). This division relates to differences in lake Kjeldahl-N and TP concentrations (Figure 12). For each lake class (crest position and vegetation zone), deep lakes tended to have lower scores on both axis one and two (Figure 15). Increasing scores on axis one corresponded to a productivity gradient with increasing total Kjeldahl-N, total phosphorus, conductivity, pH, alkalinity, and cations. Axis one scores were back correlated with environmental data and found to be negatively correlated with the ice-free date($r^2 = -0.738$). Axis two weakly correlated with elevation ($r^2 = -0.425$). These findings correspond with morphometric differences found between lakes. Deeper lakes tend to be less productive and at lower elevations within each vegetation class, both eastslope and westslope. The graph also reflects generally higher nutrient concentrations and elevation for each eastslope lake class relative to its westslope counterpart. Though these nutrient and elevation differences were not found to be statistically significant, the differences appear to be reflected in the zooplankton structure between the lake classes. The deep lakes tend to have greater proportional abundances of species such as *Diaptomus kenai* and *Diaptomus arcticus* while shallow lakes are more often have the presence or greater proportional abundance of *Diaptomus tyrrelli*.

Table 20. Crustacean zooplankton acronyms, taxa names, orders and lifestage identified in North Cascades National Park Service Complex.

Acronym	Taxon name	Order	Lifestage
ALAF	*Alona afinis*	Cladocera	Adult
ALEX	*Alona exisa*	Cladocera	Adult
ALGU	*Alona guttata*	Cladocera	Adult
ALNA	*Alonella nana*	Cladocera	Adult
ALSP	*Alona/Alonella species* (imm,unid)	Cladocera	Immature
ARHA	*Acroperus harpae*	Cladocera	Adult
BOLO	*Bosmina longirostris*	Cladocera	Adult
CDSP	Cladocerans unidentified (immature)	Cladocera	Juvenile
CEAF	*Ceriodaphnia affinis*	Cladocera	Adult
CEQU	*Ceriodaphnia quadrangula*	Cladocera	Adult
CERE	*Ceriodaphnia reticulata*	Cladocera	Adult
CESP	*Ceriodaphnia* species (unidentified)	Cladocera	Juvenile
CHSF	*Chydorus sphaericus*	Cladocera	Adult
CHSP	*Chydorus* species (unidentified)	Cladocera	Juvenile
DALO	*Daphnia longiremis*	Cladocera	Adult
DAMI	*Daphnia middendorffiana*	Cladocera	Adult
DAPH	*Daphnia* immatures (unidentified)	Cladocera	Adult
DAPU	*Daphnia pulex*	Cladocera	Adult
DARO	*Daphnia rosea* (adult males and females)	Cladocera	Adult
DASC	*Daphnia schodleri*	Cladocera	Adult
DIBR	*Diaphanosoma brachyurum*	Cladocera	Adult
HOGI	*Holopedium gibberum*	Cladocera	Adult
LPKI	*Leptodora kindti*	Cladocera	Adult
PLPR	*Pleuroxi procurvus*	Cladocera	Adult
POPE	*Polyphemus pediculus*	Cladocera	Adult
SCKI	*Scapholeberus kingi*	Cladocera	Adult
SIVE	*Simocephalus vetulus*	Cladocera	Adult
STSE	*Streblocerus serricaudatus*	Cladocera	Adult
CACO	Calanoid copepodid	Copepoda	Adult
CYCO	Cyclopoid copepodid	Copepoda	Juvenile
CYSP	*Cyclops* species (unidentified)	Copepoda	Juvenile
CYVE	*Cyclops vernalis*	Copepoda	Juvenile
DIAR	*Diaptomus arcticus*	Copepoda	Adult
DIKE	*Diaptomus kenai*	Copepoda	Adult
DILE	*Diaptomus leptopus*	Copepoda	Adult
DILI	*Diaptomus lintoni*	Copepoda	Adult
DITY	*Diaptomus tyrrelli*	Copepoda	Adult
EUAG	*Eucyclops agilis*	Copepoda	Adult
EUSP	*Eucyclops* species	Copepoda	Adult
MAFU	*Macrocyclops fuscus*	Copepoda	Adult
MASP	*Macrocyclops* species	Copepoda	Juvenile
NAUP	Nauplii	Copepoda	Immature
ORMO	*Orthocyclops modestus*	Copepoda	Adult
PAFI	*Paracyclops fimbriatus*	Copepoda	Adult
PASP	*Paracyclops* species	Copepoda	Juvenile

Figure 15. Ordination of lakes by vegetation zone and 8-m depth division based on proportional abundance of crustacean zooplankton species in each lake. Eastslope and westslope classes, and centroids for each vegetation zone with depth division are shown. Acronyms (Table 20) for taxa associated with each vegetation zone are shown. WLF = westslope low-forest; WHF = westslope high-forest; WSA = westslope subalpine; EA = eastslope alpine; ESA = eastslope subalpine; EHF = eastslope high-forest. EASH = eastslope alpine shallow. At the end of each vegetation acronym is a D (deep, > 8 m) or S (shallow) representing groups division relative to depth.

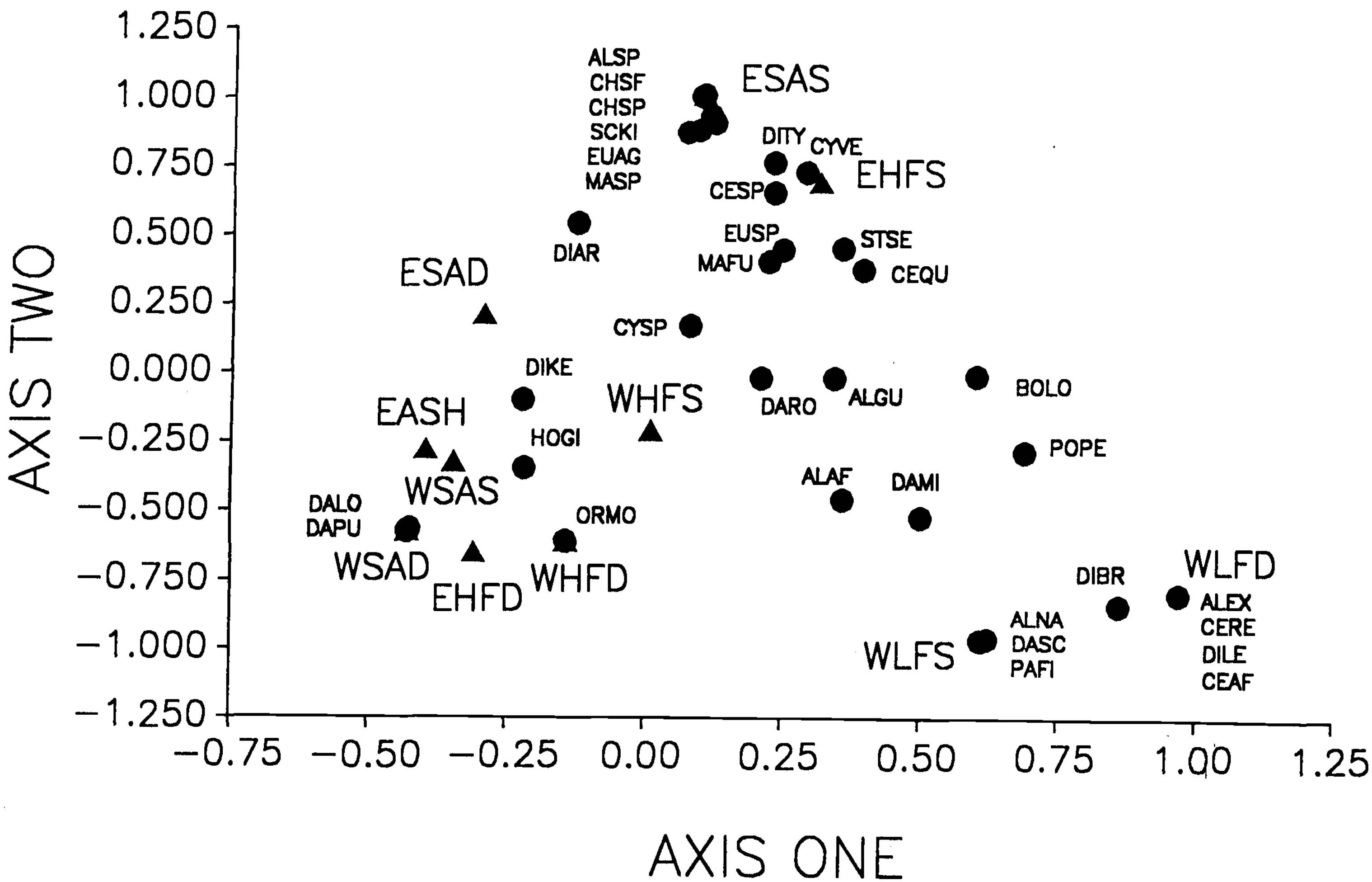

1.250
1.000
0.750
0.500
0.250
0.000
−0.250
−0.500
−0.750
−1.000
−1.250
AXIS TWO
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
AXIS ONE
ALSP
CHSF
CHSP
SCKI
EUAG
MASP
ESAS
DITY
CYVE
EHFS
CESP
DIAR
EUSP
MAFU
STSE
CEQU
ESAD
CYSP
DIKE
WHFS
DARO
ALGU
BOLO
EASH
HOGI
POPE
WSAS
ALAF
DAMI
DALO
DAPU
ORMO
WSAD
EHFD
WHFD
DIBR
WLFD
ALEX
CERE
DILE
CEAF
ALNA
DASC
PAFI
WLFS

Figure 15.

The ordination in Figure 16 suggests relationships exist between zooplankton taxa and water chemistry variables. Nutrients, conductivity, pH, alkalinity, and cations were positively correlated with axis one suggesting a productivity gradient. The most nutrient depauparate lakes (cluster 1 lakes from chemistry analysis) were found on the left side of the figure, while the highest axis-one scores belonged to productive lakes (cluster 3). Axis two was negatively correlated with vegetation class ($r^2 = -0.382$) and weakly correlated with total phosphorus ($r^2 = 0.318$) and elevation ($r^2 = 0.480$). Species identified with low nutrient conditions include *Orthocyclops modestus*, *Daphnia longiremis*, *Chydorus* species, and *Daphnia pulex*. The pattern of lake clusters from ultra-oligotrophic to productive suggests phosphorus levels are lowest in oligotrophic lakes and highest in productive lakes with mesoproductive lakes and ultraoligotrophic lakes intermediate in phosphorus concentration. The residual glacial inputs of many ultra-oligotrophic lakes may keep phosphorus concentrations in these lakes slightly elevated relative to oligotrophic lakes.

Phytoplankton

Ninety-seven taxa were identified including representatives of chlorophytes (Chlorophyta), chrysophytes (Chrysophyceae), diatoms (Bacillariophyceae), cyanobacteria (Cyanophyta), dinoflagellates (pyrrophyta), cryptomonads (Cryptophyta), and a euglenoid (Euglenophyta). Liss and others (1995) summarize the general nature of the phytoplankton assemblages in lakes from 1989–1993 relative to lake classes. Overall, Cyanophyta had the highest cell density and proportional density for lakes with 500 cell counts. Subalpine and high-forest lakes had the largest average number of taxa per year, 125 and 122 respectively, while alpine lakes had the fewest

Figure 16. Ordination of lakes by chemical cluster based on proportional abundance of crustacean zooplankton species in each lake for each cluster. Acronyms (Table 20) for taxa associated with each cluster are shown. The centroids of clusters 1–4 are labeled Clus1, Clus2, Clus3, Clus4 respectively.

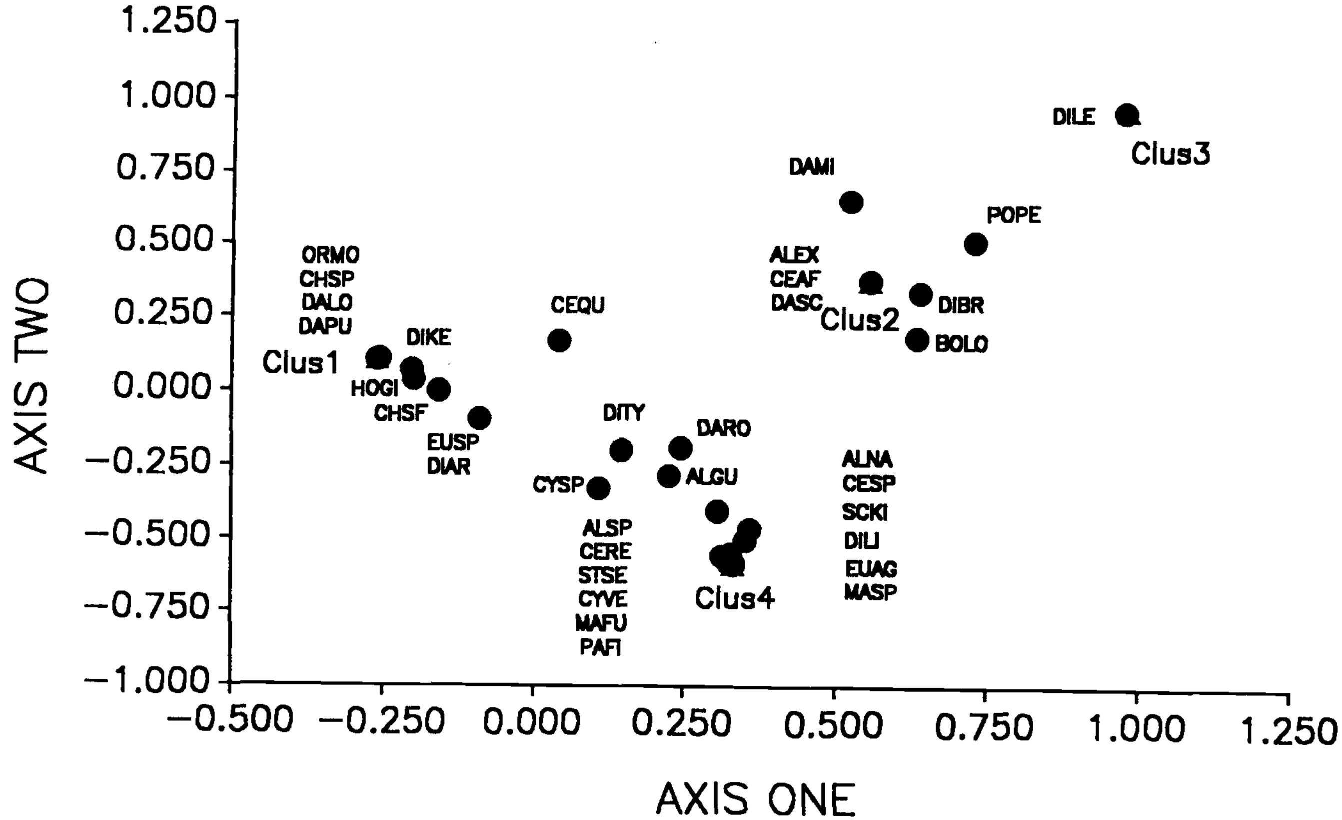

AXIS TWO
AXIS ONE
1.250
1.000
0.750
0.500
0.250
0.000
−0.250
−0.500
−0.750
−1.000
−0.500
−0.250
0.000
0.250
0.500
0.750
1.000
1.250
ORMO
CHSP
DALO
DAPU
DIKE
Clus1
HOGI
CHSF
EUSP
DIAR
CEQU
DITY
CYSP
ALSP
CERE
STSE
CYVE
MAFU
PAFI
DARO
ALGU
Clus4
DAMI
ALEX
CEAF
DASC
Clus2
DIBR
BOLO
POPE
DILE
Clus3
ALNA
CESP
SCKI
DILI
EUAG
MASP

Figure 16.

(69). Taxa numbers in low-forest lakes were intermediate (100). Subalpine and high-forest lakes were predominately composed of chrysophyte and chlorophyte taxa, while low-forest lakes were dominated by chrysophyte taxa. Chlorophyte, diatom and chrysophyte taxa were evenly distributed in alpine lakes. Pyrrhophyta, Cryptophyta, Euglenophyta, and other unknown taxa tended to be low in numbers per sample and evenly distributed across the vegetation zones.

Though variation between samples was high, plotting the mean scores of lake ordinations that were based on phytoplankton assemblage structure and grouped by chemical cluster (Table 15) provided similar results to earlier chemical analyses (Figure 17). As identified in the earlier chemical analysis, clusters ranged from those with low nutrient levels, except phosphorus (cluster 5), to clusters with much higher nutrient levels (i.e. cluster 3). Axis one represented a productivity gradient with mean nutrient and cation concentrations increasing from left to right. Clusters 5 and 3 were most dissimilar along axis one, while axis two separated out the glacially influenced lakes (cluster 5). Axis two was correlated with phosphorus (TP, $r^2 = 0.981$ and OP, $r^2 = 0.794$). Cluster's 1 and 4, which were similar to each other, had intermediate axis one values relative to clusters 5 and 3.

Analyses of 1989 phytoplankton data by Liss and others (1995) generally supported results that classification identified differing physical and chemical conditions found in lakes in the four vegetation zone classes. Lakes were divided into four groups based on the correspondence between lake ordinations and species ordinations (Figure 18). Group 3 included 5 alpine lakes, 5 subalpine lakes and a high forest lake. Group 4 was dominated by low forest westslope lakes (4) though two high-forest lakes were also included. The rest of the lakes, representing all vegetational zones, fell into groups 1 and 2. Increasing Kjeldahl-N concentrations and decreasing

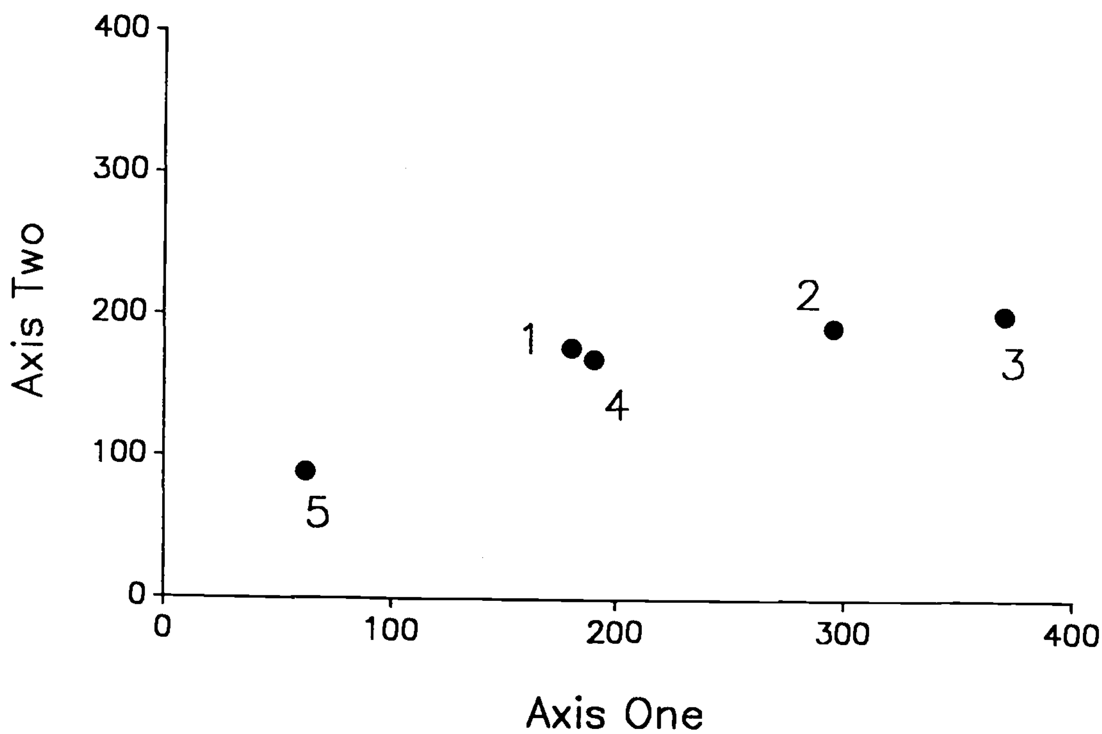


Figure 17. Distribution of chemical clusters based on the proportional abundance of phytoplankton taxa in each lake for each cluster.

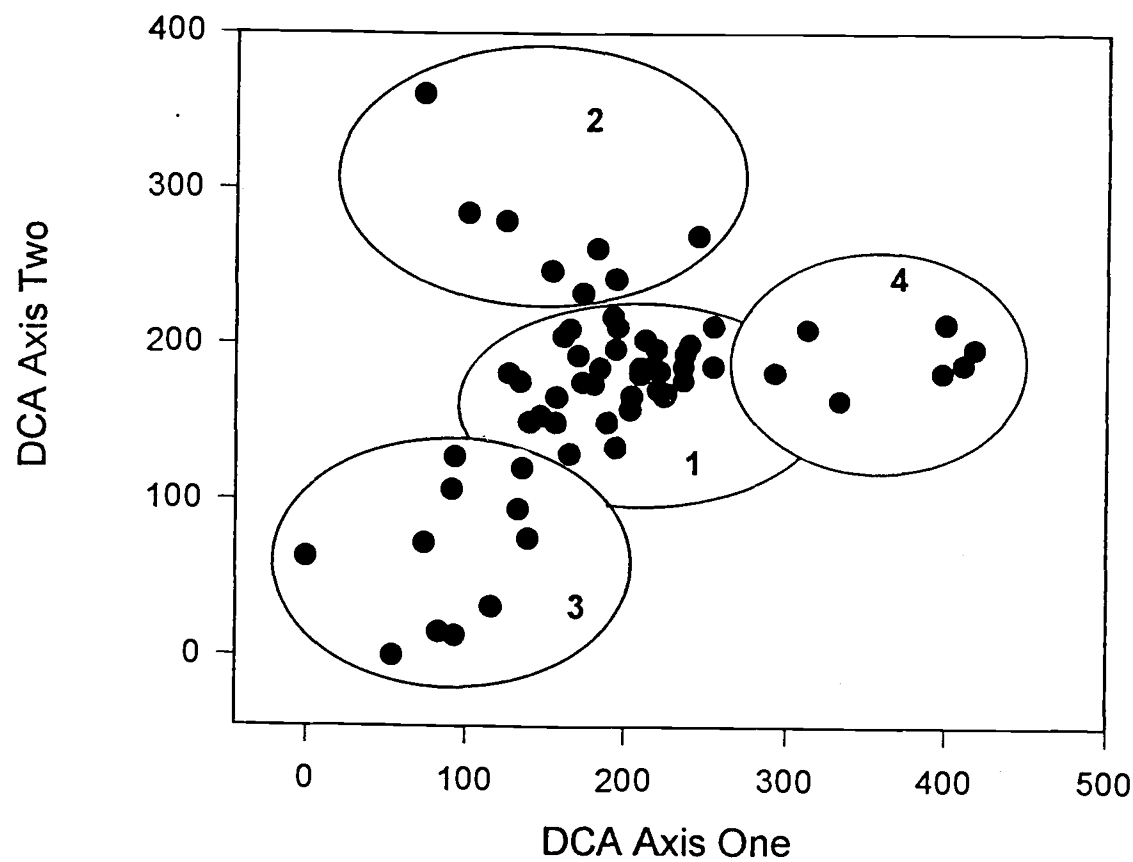


Figure 18. Ordination of lakes based on proportional abundance of phytoplankton taxa in each lake for surveyed lakes in 1989. Lake clusters are shown. Figure after Larson and others 1995, unpublished data. Used with permission of the author.

elevation corresponded to axis one scores (multiple regression analysis, $r^2 = 0.521$, $P < 0.01$), and increasing scores along axis two corresponded to decreasing concentrations of orthophosphorus and increasing water temperature (multiple $r^2 = 0.254$, $P < 0.01$). Though lakes in each cluster differed in dominant species present, cell densities and average number of species (Liss and others 1995), the pattern of differences among lakes based on their phytoplankton suggests low-forest lakes and alpine lakes are the most discrete compared to the rest of the lakes.

DISCUSSION

Utility of the NOCA Lake Classification System

The utility of lake classification depends upon its ability to order data through reduction or simplification of vast amounts of descriptive information. Three main reasons have been identified for ordering such data: 1) to gain a broad understanding; 2) to simplify complexity by identifying common factors; and 3) to predict relationships or properties for unsampled components of systems (Elster 1974). These three reasons encompassed the goal and objectives for this research.

A hierarchical watershed approach to the NOCA lake classification based on potential capacities was developed with the expectation and assumption that even within the narrow ranges of physical, chemical, and biological diversity among park lakes, interpretable ecological patterns and differences would exist between and among classes. At the first level of classification, an eastslope/ westslope division delineated a major climatic change across the park, and was shown to affect the date of ice-out, vegetation, and precipitation. At the second level, watershed vegetational classes or zones (alpine, subalpine, high forest, low forest) were identified. These zones can be compared to Chorley's (1964) "historical hangovers," landscape features developed during previous climatic regimes that are slow to change and are representative of past developmental process. Vegetation zones provided an indirect measure of local climate, soils, and moisture conditions that had influenced the physical and chemical processes occurring in the watershed and lake. The large elevation differences between some lakes within the park provided climatic diversity in a limited regional area that would otherwise be expected only across broad latitudinal ranges (Brylinsky and Mann 1973). The lowest level of the classification (lake origin) was selected to reflect differences in lake and watershed morphometry, relative persistence, and relative position in the landscape. Lake origin reflected shape and depth of lake basins, factors found important in influencing physical, chemical, and biological variables of lakes.

Although no single classification can meet all present and future needs or objectives, in my view, this approach provided a robust classification having the potential to address both research and management-related questions at multiple spatial and temporal scales. By focusing on variables that are proxies for measuring the potential capacities of lakes and their watersheds, an attempt was made to encompass the range of potential performances for each class that might be found presently and under future developmental environments. Because classes are relatively permanent, this classification can be used for long-term monitoring (decades and centuries) and still provide interpretive value for evaluating collected data. This classification provides the context for data to be synthesized and interpreted that are being influenced and operating over differing spatial and temporal scales of NOCA lakes. This hierarchical classification has used potential capacities determined within the context and time frame relative to and since the last glacial epoch. The data that has been collected thus far provides a basis for immediate interpretation of the existing condition and their watersheds at multiple spatial scales and provides the basis for future interpretations of long-term data sets. However, a low frequency, evolutionary event (such as a new glacial epoch) would change the potential capacity of each of the defined classes and diminish the present classifications' use as a tool for explanation of observed phenomena.

This research has 1) provided a broader understanding of mountain lake systems in NOCA relative to physiographic characteristics of the terrestrial and lake environments; 2) helped to identify the existing diversity of lake types parkwide; 3) related physical and chemical properties of lakes to physiographic characteristics of the terrestrial environment; and 4) provided ecologically meaningful generalizations about NOCA lakes, their watersheds and the park.

The utility of the lake classification system used at NOCA can be illustrated by comparing it with other lake classification systems. During the past 60 years, limnologists developed several lake classification approaches that addressed physical attributes, morphometry, nutrients, biological organisms (criteria), or combinations of these variables on very diverse groups of lakes. Larkin and Northcote (1958) sampled a large group of British Columbia lakes with a wide range of mean depths, and they determined that conductivity decreased with increasing mean depth. The range of mean depths among NOCA lakes was narrow in relation to the lakes studied by Larkin and Northcote, and the relationship between mean depth and conductivity at NOCA was weak and not significant ($r^2 = -0.123$). George and Maitland (1984) used lake basin morphometric characteristics as the basis of classifying lochs in Scotland that, unlike NOCA, differ little in climatic extremes. Mean depth was found to be a good indicator of fish production in Canadian lakes, but overall these lakes were much larger than those existing at NOCA (Rawson 1955). Pennak (1958) used elevation to classify lakes in the Colorado Rockies that were similar with respect to basin geology, origin, and aspect. In the North Cascades, however, aspect played an important role in determining the vegetation class of lake watersheds and in the date lakes became ice-free. Lewis (1983) classified lakes of varying climates worldwide using temperature and mixing. However, using this classification, NOCA lakes would be grouped into a single class (dimictic), though some of the lakes may be amictic in some years.

The primary focus of a number of other lake classification systems has been the rate of nutrient loading. Vollenweider (1968) determined that loading rate of total phosphorus was an indicator of the trophic status of lakes. Almost without exception, NOCA lakes are limited to oligotrophic or ultra-oligotrophic groups. The range of total phosphorus concentrations in NOCA lakes was minimal in comparison to the range for lakes studied by Vollenweider. Schindler (1971) determined that concentrations of nitrogen and phosphorus in lakes in the Experimental Lakes Area (ELA) were associated with the ratio: [lake and watershed area /lake volume] . Unlike NOCA, the ELA area is of uniform topography, vegetation, and geology. Schindler found linear relationships between concentration of nutrients over a relatively limited range of watershed-to-volume ratios (0 to 7). At NOCA the range of watershed-to-volume ratios was much larger than for the ELA lakes, and the relationships between concentration of nutrients and watershed to volume ratios were curvilinear. Results from this research suggest that as the watershed-to-volume ratios exceed seven, concentrations of nutrients like nitrogen begin to exponentially decrease in the water column due to flushing rate dilution.

Biological approaches to lake classification have existed for most of the century. Thieneman (1909) grouped a diverse range of lakes by the presence or absence of specific chironomid species. NOCA lakes include a very narrow range of these chironomid lake types. Tonn and Magnusson (1982) classified Northern Wisconsin lakes based on the number of fish species present. Fish are not indigenous to NOCA lakes, and thus species diversity of fish is meaningless as an indicator of either environmental, trophic or developmental conditions in park lakes. Due to the inherent weaknesses (presence/absence, other complicating factors) of using single organism trophic indicators, Round (1958) and Nygaard (1949) developed phytoplankton quotients to classify lakes. However, the species they used were not important in NOCA phytoplankton assemblages, and Shapiro (1975) suggests that quotients such as these provide little information regarding the condition of the lake. Still other researchers have classified lakes based on their zooplankton structure (Sprules 1980, 1984) or grouped lakes according to the presence of particular taxa (Liss and others 1995), yet zooplankton assemblages may be more reflective of present predator/prey relationships than of physical and chemical differences reflecting historical or evolutionary trophic relationships, aspects important to the objectives of this research.

A number of lake classifications have combined chemical and physical approaches. The Morpho-Edaphic Index (MEI) developed by Ryder (1965) combines mean depth and total dissolved solids (TDS) to classify lakes for potential fish production. The index was originally intended for lakes greater than 260 ha in surface area, less than 600 m in elevation, with low flushing rates and inorganic turbidity, and within an area with relatively homogenous environmental conditions. Climatic conditions and limnological characteristics of NOCA lakes violate each of these restrictions. The Trophic State Index (TSI) created by Carlson (1977) was developed using a set of lakes with a very wide range of Secchi disk transparencies and concentrations of chlorophyll and total phosphorus. Chlorophyll was used as an index of algal biomass. The TSI is not appropriate for glacial systems or lakes of extreme clarity (Carlson 1977). Algal biomass is very low in NOCA lakes (Liss and others 1995), and the water is extremely clear (Secchi disk visibility extends to the bottom in many lakes). Thus the TSI is of little value as a method for classifying NOCA lakes.

From a world-wide perspective, NOCA lakes are limited in area, depth, geomorphic origin, and nutrient diversity. Around the world, lakes range in area from the largest, Lake Superior (833,000 ha), to small ephemeral bodies of water, and in depth from Lake Baikal (1620 m) to ponds < 1 m in depth (Wetzel 1983). Locally, some lakes found just west of NOCA in the morainal deposits of the Puget Sound lowlands (e.g. Lake Washington, 8959 ha, 65 m deep, [Edmondson 1991]; Whatcom lake, 2024 ha, 101 m deep; [Wolcott 1964] are considerably greater in surface area than the largest NOCA lake (Silver lake 65.1 ha, approx. 137 m) though not deeper. Lake Chelan (13,397 ha, 488 m deep [Wolcott 1965]), the largest and deepest lake in Washington, just enters NOCA at the south-east corner of the park and extends south-east for approximately 80 km draining into the Columbia River. The potential for large lakes like Lake Chelan, Lake Washington and others to be created inside the park was minimal. This is primarily a result of steep topography. The potential for large tectonically formed lakes exists along the Straight Creek fault and particularly in the Methow Graben east of the park, but no basins have formed over the short geological time frame of the existence of the North Cascades Mountains.

Hutchinson (1957) identified eleven major categories of lakes worldwide based on their origins: 1) tectonic basins; 2) lakes associated with volcanic activity; 3) lakes formed by landslides; 4) lakes formed by glacial activity (ice-dammed, glacial rock basins, morainic and outwash dams, drift basins); 5) solution lakes; 6) lakes formed by fluvial action; 7) lakes formed by wind; 8) lakes associated with shorelines; 9) lakes formed by organic accumulation; 10) lakes formed by the behavior of higher organisms; and 11) lakes formed by meteorite impact. Seventy-six subdivisions were determined from these 11 categories of lakes, yet only a few subdivisions encompass the entire diversity of origins of NOCA high lakes (i.e. glacial rock basins, slumps, kettle (drift), morainic dams).

In summary, these comparative lake classifications were inadequate for the NOCA project. Key reasons for these conclusions were the limited ranges of surface areas, depths, geomorphic origins and water qualities of the lakes. Limited trophic ranges further increased the difficulty of developing a potentially meaningful classification, because all lakes were either ultra-oligotrophic or oligotrophic as determined from nitrogen and phosphorus concentrations (Vollenweider 1968).

Application of the NOCA Lake Classification System

Physical and Chemical

Although NOCA lakes exhibited a relatively narrow range of water qualities and concentrations of nutrients and diversity of biological species relative to world-wide diversity (Wetzel 1983), within this narrow set of ranges, classification was able to order the diversity. Based on concentrations of nitrogen and phosphorus, the two most productive lakes were marginally mesotrophic, whereas the majority of lakes were either ultra-oligotrophic or oligotrophic (Likens 1975). None-the-less, hydrologic crest position, vegetation zone, and basin origin were relatively important variables influencing physical and chemical characteristics of NOCA lakes. The upper limits of individual vegetation zones were located at higher elevations on the eastslope than on the westslope, a result of the sharp west-east climate gradient (Franklin and Dyrness 1973). These climatic differences essentially excluded the alpine zone from the eastslope of the hydrologic crest. Watershed vegetation development, from alpine to low forest, was associated with increased lake water temperature, decreasing elevation, and earlier dates of ice-out, though vegetation zones did not significantly order many water chemistry parameters. Alkalinity, pH, Kjeldahl-N, and certain cations

(Ca, Mg, Na) decreased from the low forest to the alpine zone on the westslope. However, alpine lakes receiving glacial outwash were high in total phosphorus, and several low-forest lakes in sedimentary lithology had elevated water quality (pH, alkalinity, conductivity) relative to those lakes lacking this rock type in their watersheds. For a given vegetation zone, lakes east of the hydrologic crest iced-out earlier than lakes west of the crest. Furthermore, lakes in west facing watersheds became ice-free earlier than did lakes in east facing watersheds in each vegetation zone. Some morphogenetic classes were found in all vegetation zones (cirques, troughs, ice scour, and moraine-dammed lakes), whereas others were restricted in distribution to the forest zone (kettle, slump). Concentration of Kjeldahl-N and total phosphorus varied with lake depth and flushing rate.

Local climatic differences related to aspect, precipitation, and crest position influenced the elevational range of local vegetation zones, and other physical, chemical and biological parameters of lakes and watersheds. Vegetation zones were assumed to be representative of these local climatic conditions. Lakes with the highest concentrations of nutrients (except NO_3) and water quality (temperature, pH, alkalinity, and conductivity) were in the low-forest zone, which had the latest successional vegetation, greatest potential for water and soil interactions, and have been deglaciated for the longest period of time. However, concentrations of total phosphorus in turbid alpine lakes receiving glacial outwash were comparable to those of low-forest lakes. Phosphorus concentrations in subalpine lakes were low relative to those in turbid alpine lakes because glacial inputs were much reduced, and phosphorus, with generally low solubility in water, readily precipitates to the sediments (Hem 1989). Eastslope watersheds tended to be steeper than westslope watersheds. The higher levels of moisture westslope may have caused greater weathering leading to less steep relief. Subalpine watersheds were steeper than forest watersheds, perhaps reflective of differential moisture type and availability for weathering. In the low forest lakes and watersheds, weathering of soils and bedrock occurs for a longer period each year relative to the subalpine zone that is covered by snow and ice for most of the year.

Epilimnetic temperatures and the date lakes became ice-free were shown to vary relative to vegetation zone, crest position, and aspect. However, annual climatic differences also affected seasonal patterns. Lakes with late ice-free dates (i.e. alpine lakes) were generally colder throughout the ice-free season than lakes that became ice-free earlier in the season. This is related to heat budgets and the availability of clear sky insolation which peaks on the summer solstice, June 21, in northern temperate zones.

Lake origin was useful in identifying potential differences in long term persistence, basin location, and the diversity of lakes parkwide, but was not as useful to differentiate lake size or depth. Lake basins formed by erosional processes may be more persistent than lakes created by depositional land forms (Table 5). The amount and rate of infilling is a function of both origin and lake age. In the low-forest zone, trough lakes no longer cover entire valley floors as relatively young alpine trough lakes often do, and they tend to be shallower than alpine trough lakes. This seems contrary to general findings that the biggest, deepest lakes are created at lower elevations. Within NOCA, however, the biggest, deepest lakes occurred in the alpine zone. Relatively shorter-lived slump lakes originate from a rotational slip in deep seated soils, and therefore, could potentially occur only in the forest zone in NOCA, the zone which had the greatest soil maturity and depth. Surprisingly, kettle lakes occurred in one park drainage though they are generally restricted to ground moraines deposited across the continental plains. Other examples of ground moraine lakes are found in the Puget lowlands west of the park boundary. Morphogenetic origin, which was chosen as a proxy for size (surface area) and depth (since all lakes could not be field surveyed), did not clearly segregate lakes by depth. Each origin class was found to have high variability though consistent trends were noted. For the lakes formed by glacial scour, troughs tended to be deeper and larger than cirques, and cirques deeper and larger than ice-scour lakes in the alpine and subalpine zones. In the forest zone, the pattern was consistent for surface area but not depth. The decreasing depth of trough lakes, possibly caused by high rates of deposition of mineral and organic inputs from permanent inlets, has hastened ontogeny and altered the alpine-subalpine pattern such that trough lakes, initially the deepest lakes of the alpine zone, become the shallowest lakes in the forest zone.

Though differential weathering of gneiss, granite, schist, basalt and greenstone is well documented (Birot 1968, Linton 1972, Matthes 1972, Ollier 1984), lithology did not appear to be a significant contributor to chemical differences in NOCA lakes except for those lakes found in greenstone. Most lakes were found in gneiss or granite, two lithologies differing only by slightly rearranged crystalline structure in some instances. The chemical products of weathering for granite and gneiss may be very similar (Hem 1989). Significant differences in nutrient concentration were not found between these two rock types. These extremely young, shallow soils also minimize differences between rock types because water only contacts soils for short periods of time. During this brief contact period, few minerals are dissolved into solution and transferred to the lake water column. Consequently, bedrock lithology may make a greater difference to lake basin substrate composition rather than the chemical composition of the lake. The tendency of large crystal bearing granitic lithology to spall and decompose into granular fragments as it weathers versus decomposition into angular fragments for metamorphic rock with finer crystals like gneiss (Ollier 1984), may influence benthic substrate and consequent macroinvertebrate assemblages.

Biological

The distribution of fish in NOCA lakes resulted from anthropogenic stocking and was not related to evolutionary colonization of park lakes, since all high lakes in the park were naturally fishless. However, interpretation of fish distribution relative to classification variables is still illuminating. Lakes stocked with fish were significantly larger and deeper than unstocked lakes. Selected stocking of large deep lakes minimizes the risk of winter die-off due to oxygen deprivation or freezing of the entire water column. while lakes are frozen over. Generally, permanent inlet or outlet streams provide potential spawning areas for trout in the deepest and largest lakes. Reproducing populations of fish tend to occur in such setting. A higher percentage of eastslope lakes were stocked, reflecting easier access to the lakes and potentially greater fishing use. Forest lakes were stocked at a higher rate than subalpine lakes, perhaps due to accessibility and potential food sources for fish.

Crustacean zooplankton assemblages exhibited no patterns relative to eastslope or westslope climatic differences, suggesting that many species are dispersed throughout NOCA, but zooplankton assemblages did show a much greater correlation to physical and chemical characteristics. Factors including water temperature (Byron and others 1984, Stoddard 1987), lake elevation (Reed and Olive 1958, Patalas 1964, Anderson 1971), and water chemistry (Byron and others 1984, Stoddard 1987) have been found to influence zooplankton distribution and abundance. Zooplankton assemblages in high forest and subalpine lakes were poorly predicted using discriminant analysis. This was not unexpected because of the high variability and overlap of physical and chemical factors of lakes in these zones. Prediction of assemblages in alpine and low-forest zones were much clearer, a consequence of the unique physical and chemical differences of these zones relative to subalpine and high-forest zones.

The relationship between lake chemistry and depth was also reflected in the structure of zooplankton species for specific lakes. Zooplankton assemblages consistently correlated with nutrient or productivity gradients in ordinations (Liss and others 1995). Though lake chemistry of a specific vegetation class did not differ significantly from eastslope to westslope, subalpine eastslope lakes tended to have slightly greater concentrations of nutrients (TKN, TP), water quality (pH, alkalinity, conductivity) and cations (Na, K, Ca, Mg), and the differing zooplankton assemblages found in these lake classes reflected these slight differences. For example, *D. tyrrelli*, which is found in lakes with higher concentrations of Kjeldahl-N, predominated in these shallow eastslope subalpine lakes (Liss and others 1995). A few species (*Orthocyclops modestus*, *Daphnia longiremis*, *Chydorus* species, and *Daphnia pulex)*, rare except for *Chydorus* sp., were found to exist (Figure 16) in relatively lower nutrient conditions relative to other species. These species may be more efficient at obtaining food or are possibly poor competitors in lakes of low productivity such as those found at NOCA. Higher productivity may favor coexistence in other regions. Sprules (1972) found that *D. pulex* outcompeted *D. rosea* in shallow ponds in Colorado. At NOCA, however, differing environmental and physical factors may be controlling species structure. *Diaptomus kenai* and *Daphnia rosea* were found to be ubiquitous and appeared tolerant of a wide range of chemical and physical conditions (Liss and others 1995). Classification identified westslope low forest lakes as highly unique in physical and chemical factors relative to the other lake classes, and a number of taxa (*Alona exisa, A. nana, Ceriodaphnia affinis, C. reticulata, Diaphanosoma brachyurum, Daphnia schodleri, Paracyclops fimbriatus, Diaptomus leptopus*) were found only in these lakes. Higher productivity and greater habitat diversity (Liss and others 1995) may be supporting the higher species diversity in these lakes.

Incomplete annual sampling across vegetation classes in any one year did not allow meaningful analysis of phytoplankton using the proposed lake classification beyond the 1989 parkwide survey when all vegetational classes of lakes were sampled. However, in 1989, most lakes were sampled only once, precluding any analysis of annual variability, which is likely high in NOCA lakes (Larson and others, in prep). Annual variation, which was due in part to the inconsistent period between the date of ice-out and the sample date, annual wet or dry cycle variation, and potential fire influences, influenced analyses by Larson and others (in prep) who found dominant species to completely change from one year to the next for selected lakes. However, cyanobacteria were found to increase with decreasing elevation, and densities of chrysophytes and chlorophytes were high at high elevation.

Classification by crest position provided limited utility for discerning differences in phytoplankton assemblages, and vegetation-zone classes were only marginally better. Alpine lakes had the fewest species while subalpine and high forest lakes had the largest average number of species. Intermediate values of species diversity for low forest lakes may be more indicative of sampling timing rather than true differences between this class of lakes and the high-forest and subalpine classes. Phytoplankton diversity was found to decrease seasonally for lakes sampled multiple times (Liss and others 1990). Sampling began in late June, though most low-forest lakes had been ice-free for a month or more. Thus, initial sampling of phytoplankton in low forest lakes may have been similar to later season sampling for other lakes at NOCA. As in other analyses, the two groups of lakes that had the most distinctive phytoplankton assemblages were westslope alpine and low forest lakes which were the most dissimilar classes of lakes.

An analysis of phytoplankton patterns based on the chemical clusters derived in the water chemistry analysis did not increase the effectiveness of defining discrete assemblages of phytoplankton, though a number of researchers have identified a relationship between phytoplankton and nutrients (Pechlaner 1971, Ilmavirta and others 1984, Larson and others 1995). Other factors including days since the lake had become ice-free, temperature, grazing by zooplankton or other invertebrates may be influencing phytoplankton structure.

Further support for the utility of hierarchical classification was provided by Hoffman and others (in press), who found the structure of benthic macroinvertebrate assemblages in NOCA to be consistent with crustacean and phytoplankton results. Species diversity was highest in forest lakes and lowest in alpine lakes and paralleled vegetation zone-substrate relationships. Classification of lakes by crest position and vegetation zone was found to support the relationships between terrestrial characteristics and the benthic macroinvertebrate assemblages of NOCA lakes. Higher pH levels associated with vegetational development in forest zone lakes was postulated as preventing the establishment of a dytiscid beetle, *Potamonectes griseostriatus*, and pH and water hardness requirements limited gastropods to three westslope, low-forest lakes.

NOCA Lake Classification Relative to Lake Development for NOCA

Lake classification systems identify and organize fundamental similarities and dissimilarities among groups of lakes. The hierarchical classification developed here identified those similarities and differences in physical, chemical, and biological characteristics among and between classes of NOCA lakes, lakes that, from a broad perspective, were very similar. The consistent pattern from all analyses showed only a small percentage of the lakes (alpine and westslope low-forest lakes) to be distinct; the rest of lakes were very similar ultraoligotrophic to oligotrophic high-mountain lakes.

The varied lithologies within NOCA had different potentials for physical and chemical weathering, nutrient availability, and vegetation and soil development. At this early stage in the development of most lakes and their basins, few significant differences because of variations in bedrock were found. Only the lakes found in greenstone appeared to have chemical differences directly attributable to geology.

Developmental pathways for the three major vegetation-zone classes of lakes identified at NOCA (alpine, subalpine, and forested) are highly dependent upon their developmental environment (Figure 19). After deglaciation, all lake basins were theorized to begin as alpine-like systems. Localized climate resulted in different developmental environments (DE_1, DE_2, DE_3) for each lake which influenced their progression into other lake types. A basin in DE_1 will not develop beyond an alpine type system due to environmental constraints (e.g. high elevation, west slope). In DE_2, the system progresses from an alpine state to a subalpine state, but is unable to develop further. Lakes in DE_3 are able to develop through alpine and subalpine-like stages to lakes found in forested watersheds. Present day developmental stages (classes) are surrounded by a dashed line (Figure 19). Some stages (outlined with a dashed line) of lake development will not occur in particular developmental

Figure 19. The development of lake and watershed systems is mutually dependent upon a system's potential capacity and its developmental environment (DE). States or stages of development are alpine, subalpine, and forest. Environments DE_1, DE_2, and DE_3 lead to all three stages present today because of differing rates of development. Present environments constrain some alpine and subalpine lakes from further development in the future.

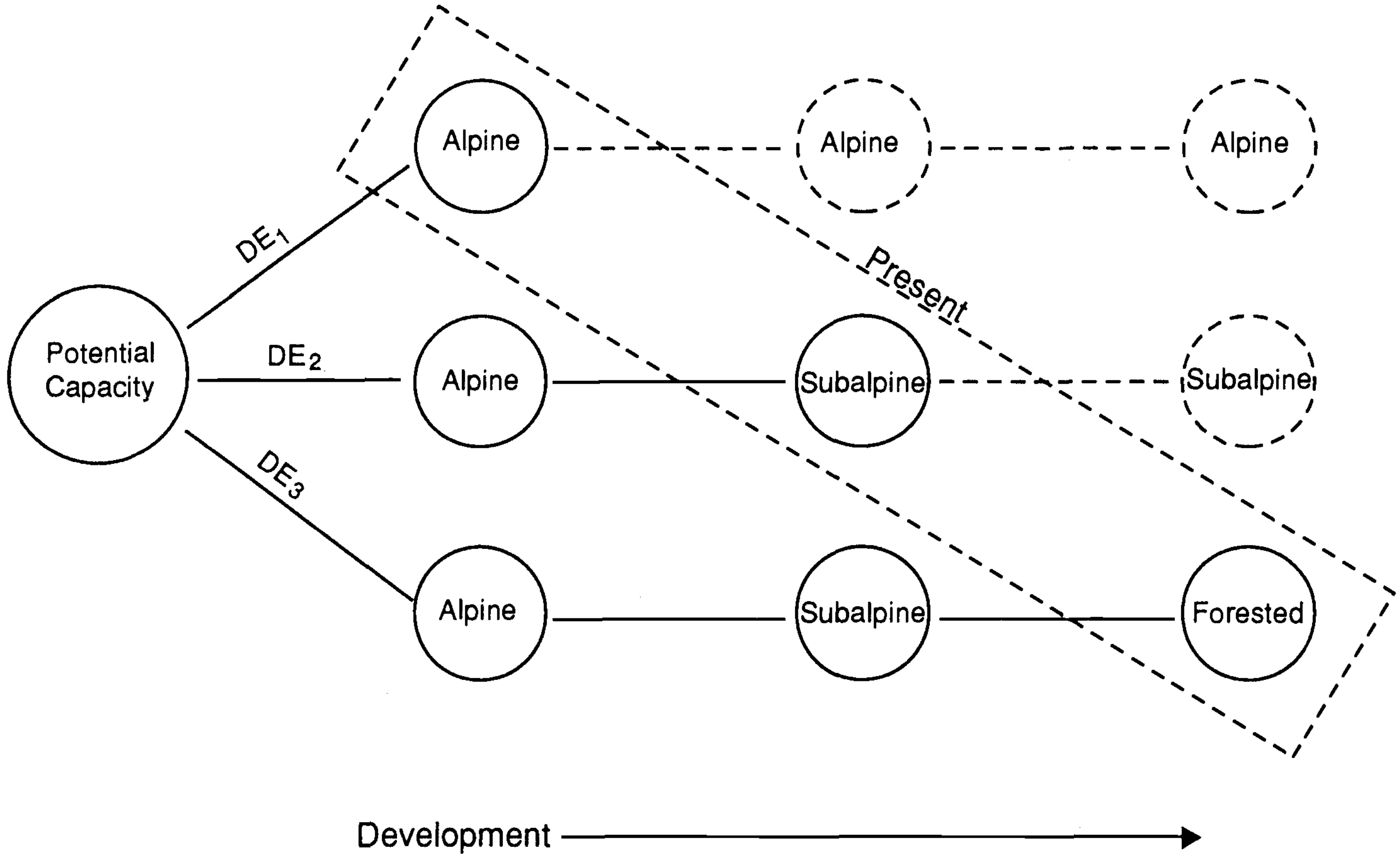

Potential
Capacity
DE1
DE2
DE3
Alpine
Alpine
Alpine
Alpine
Alpine
Subalpine
Subalpine
Subalpine
Forested
Present
Development

Figure 19.

environments. These lakes are constrained by their developmental environment to remain in an existing state. However, If any of the developmental environments were to change, lakes in that new environment would take a corresponding developmental pathway.

Within each vegetation class (alpine, subalpine, forested), multiple stages of development were identified (Figure 20). Alpine lakes began as glacier filled basins. Post glacial lakes are turbid, influenced by glaciers active within the lake watershed. During this period, high levels of phosphorus are found in the water. Late stage alpine lakes, denoted as clearwater (CW), no longer are as influenced by glacial inputs and become more transparent. If lakes progress towards what is considered a later developmental stage, alpine-like systems shift to subalpine-like systems. The latter have greater soil and vegetation development. Early stages (ES) of subalpine vegetation development include heather meadow complexes. These are then followed by tree-clump/meadow mosaics, coined "parkland" by Franklin and Dyrness (1973). Fire disturbance, together with climate, may maintain a parkland type watershed. Depending upon the effect of elevation and aspect on local climate, a lake and its watershed may continue to develop towards a forested stage or remain at the subalpine stage (Figure 20). For watersheds found in a forested state, two progressive stages of development are recognized, open and closed forests (Figure 20). In the hierarchical classification, delineation by high-forest and low-forest divisions proved more explanatory. Fires,landslides, and avalanches were found to occasionally reset numerous watershed and lake systems back toward a more open, forested stage of development. However, development is viewed primarily as occurring in a single "forward" direction (ontogeny) in which lakes continually increase in productivity and watershed basins slowly increase in soil maturity and vegetative growth (Wetzel 1983).

Figure 20. Each stage of development (alpine, subalpine, forest) can be subdivided into more detailed stages. Under DE_1, lakes develop through a clearwater phase. Developmental environment 2 (DE_2) allows development from early subalpine (heather meadows) to parkland. Disturbances such as fire can maintain a parkland state. Developmental environment 3 (DE_3) has two stages, open forest and closed forest. Development can potentially evolve from any present stage of development towards a more alpine-like (glacier filled basin) stage, if the climate were to cool and initiate a new ice-age. This evolutionary development would create a new lake if the basin were rescoured by a glacier, reexposed, and then filled with water following glacial recession.

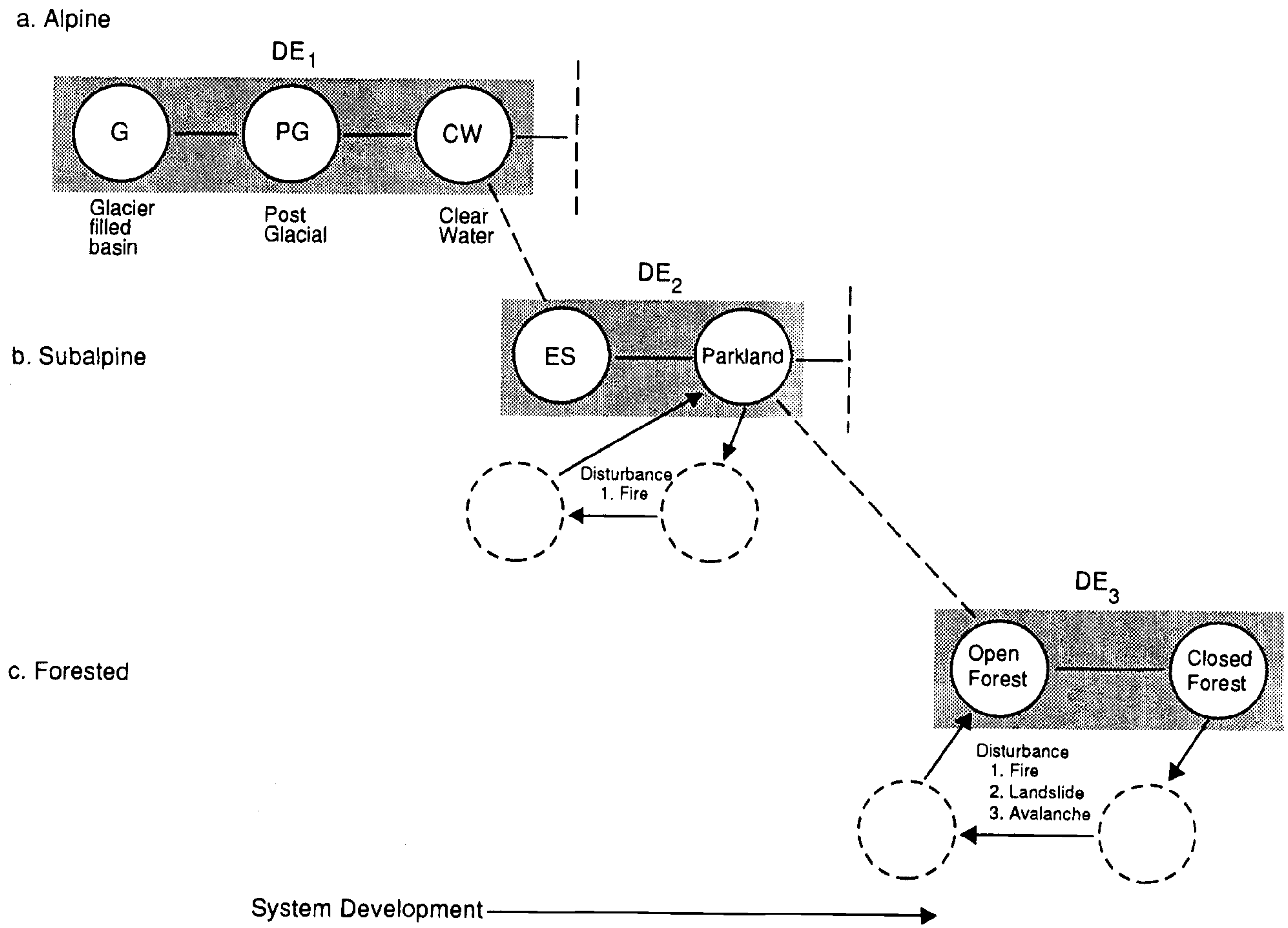

a. Alpine
DE_1
G
PG
CW
Glacier filled basin
Post Glacial
Clear Water
DE_2
b. Subalpine
ES
Parkland
Disturbance
1. Fire
DE_3
c. Forested
Open Forest
Closed Forest
Disturbance
1. Fire
2. Landslide
3. Avalanche
System Development

Figure 20.

Based on the past geologic record for this region, it is not unforeseen that another glacial period will occur (Porter 1976). If this causes glacier recurrence or advancement, watersheds and lake basins may be scoured to bedrock, completely erasing present developmental conditions in the basin. In this scenario, as glaciers receded again, lake basins would reappear exhibiting alpine-like characteristics, even if the basin had previously been a productive lake in a forest-filled watershed.

This generalized view of lake development helped to explain physical differences between alpine–, subalpine– and forested–basin lake classes, and indirectly determined differences in the present realized capacities of each class by identifying differences in the ranges of many watershed and lake performances. Lakes in these three developmental stages were found to have differences in timing and duration of ice-out, hydrology, watershed soil and vegetation development, nutrient and cation availability, basin morphology, and lake habitat.

The alpine landscape is severe, a cold, rocky, barren, desiccated zone covered by ice and snow for much of the year. The local environment for these lakes is not moderated by soils or surrounding vegetation. Lake watershed relief tends to be steep, except for those lakes perched on ridgetops. Water retention in the basins is minimal—except in frozen form—since soils are thin and predominantly mineral or nonexistent, and steep relief facilitate routing of water through the watershed. Lake ice-free date in this hostile environment comes late in the summer season (usually August at NOCA) if at all some years, and soils and vegetation development are minimal. These systems are generally restricted to the higher elevations in the headwaters of drainages and consequently, tend to have smaller watersheds, fewer permanent inlet streams, and cooler temperatures relative to forested watersheds at lower elevations in the drainages. Steep-sided, east-facing basins have maintained local climates that allow some alpine lakes to exist at relatively low elevations (e.g. Moraine 1328 m; MSH-1 1159 m; Azure 1237 m). These lakes will be especially interesting to watch in the context of potential global climate change. Low elevation alpine systems may be the most vulnerable to increased air temperatures.

Alpine lakes are typified by a lower diversity of biological species relative to forest-basin lakes, low nutrient inputs, except for phosphorus, and limited species diversity and abundance for phytoplankton and zooplankton. Crustacean zooplankton species (*D. kenai, D. pulex, D. arcticus)* are few in number and diversity or nonexistent, and phytoplankton diversity (primarily chrysophyte and chlorophytes) is limited as well. Taxa that are present must be cold-adapted species, tend to be large in size, and are members of relatively simple biological communities. Depressed trophic levels, low temperatures, a minimal ice-free period for seasonal growth, and few prey items combine to make alpine lakes inhospitable to fish, salamanders, and most other vertebrate species since these lakes have a very limited ice-free time for seasonal growth.

Under favorable (warmer) climatic conditions, lake development progresses from the alpine to the subalpine stage. Increasing soil depth and maturity leads to enhanced retention of ground water which increases mineral weathering and nutrient liberation to lakes from bedrock. In a subalpine climatic regime, lakes become ice-free earlier in the year than in alpine systems but later than forest lakes. Consequently, subalpine lakes tend to warm up earlier than alpine lakes which increases the potential species pool of colonists. Infilling processes such as colluvial transport, avalanches, and stream transportation add organic as well as inorganic materials to the lakes. The greater snow-free period of time provides increased opportunity for watershed vegetation growth. These more favorable conditions eventually lead to a parkland mosaic (Franklin and Dyrness 1973), a mixture of meadows and stringers of trees which provides added organic input to lakes in the form of leaf litter and woody debris.

Subalpine lakes, intermediates between alpine and forested basin lakes, range from nearly alpine-like systems to almost high-forest systems. The high degree of overlap with these classes for physical and chemical variables verifies that all these influencing parameters are gradient in nature, even though a specific watershed may be labeled subalpine. Glacial influence may alter physical and chemical parameters to make a lake more alpine in nature. Depending upon elevation, aspect, and crest position, subalpine lakes tend to have characteristics that more closely resemble either alpine or forest lakes. On the warmer eastslope, subalpine lakes have nearly replaced alpine lakes. Only a few still exist under our present climatic regime. Subalpine lakes are intermediate in temperature, alkalinity, pH, conductivity and nutrients relative to forest and alpine lakes. Since phosphorus precipitates to the sediments and glacial inputs are decreased or no longer present in subalpine lakes, phosphorus levels tend to be the lowest of all park lakes. Additionally, no macrophytes are present to return the phosphorus to the water column. The lakes tend to have predominantly mineral substrates (Hoffman and others in press), while organic components consist of coarse and fine wood as well as herbaceous material. Avalanche chutes appear to be the primary movers of limited woody debris into these lakes. Eastslope or westslope subalpine lakes are quite similar with the exception of higher phosphorus and Kjeldahl-N levels in some shallow, eastslope lakes.

Biological assemblages respond to the higher degree of variability in subalpine physical and chemical characteristics relative to the alpine zone with increased diversity. Longer periods of open water and warmer temperatures provide a greater opportunity for colonization of lakes and seasonal development of biological communities including flora and fauna. Warmer water temperatures further enhance physiological processes. Vertebrate predators are able to persist in the more complex communities found in subalpine lakes because of a larger and more complex food base than alpine lakes. Phytoplankton species dominating subalpine lakes includes chlorophytes, chrysophytes and cyanobacteria (Liss and others 1995). In deep, cold subalpine lakes, large zooplankters such as *Diaptomus kenai*, *Diaptomus arcticus,* or *Holopedium gibberum* dominate (Liss and others 1995). Warmer and shallower lakes may contain the smaller *Diaptomus tyrrelli*, particularly when vertebrate predators are found in the lakes (Liss and others 1995). While only 20% of the benthic macroinvertebrate taxa were found in alpine lakes, 59% occur in the subalpine zone (Hoffman and others in press). Taxonomic groups represented in the subalpine are diverse and include amphipods, plecoptera, tricoptera, and sphaeriids, in addition to hirudinea, ephemeroptera, nematodes, oligochaetes and turbellaria, all of which were present in all zones (Hoffman and others in press).

Under more temperate (warmer) climatic conditions with a long enough snow-free period for tree establishment in the warmest regions of the park, the potential exists for watersheds to develop to a forest state. Warmer temperatures lead to a reduced period of winter snowpack, increased amount of vegetation, greater soil nutrient concentrations and accumulations, and soils with higher levels of organic matter. Increased soil/water interactions create elevated nutrient concentrations delivered to lake via inlets and groundwater. Infilling processes carrying suspended sediments and organic inputs, further reduce the mean depths of lakes, particularly in trough lakes which tend to have permanent inlets. Fed by the more abundant groundwater, a greater number of permanent inlet and outlet streams exist. Weathering processes such as frost riving and colluvial raveling have decreased watershed slope relief, further increasing the potential for soil and water interactions. Woody debris is an important component of nutrient storage in these lakes and helps to further diversify the habitat for biological species.

Forest lakes are found in the lower elevations of the park, often in valley bottoms away from ridge slopes since colluvial infilling processes tend to push lake shorelines towards the middle of valleys. These lakes are the most productive in the park, though they are still not nutrient-rich lakes relative to productivity scales based on lakes the world over. Forest lakes, particularly the low-forest lakes, are high in temperature, pH, alkalinity, conductivity, Kjeldahl-N, ammonia-N and total phosphorus, and cations. The lakes are warmest, become ice-free earliest in the season, and contain the most complex zooplankton species assemblages (Liss and others 1995) and benthic macroinvertebrate assemblages (Hoffman and others in press) in NOCA. The phytoplankton are dominated by cyanobacteria in low-forest lakes and have little diversity. Macroinvertebrates, however are very diverse with taxa including tricopterans (*Limniphilus*, *Halesochila*, *Polycentropus* sp.) Baetid ephemeropterans (*Callibaetis)*, and odonates occupying many diverse habitats (Hoffman and others in press). These species have a higher tolerance for warmer water and many are adapted to the fine soft organic detrital bottoms of the lakes. Liss and others (1995) find that common zooplankton species in the NOCA forest zone include the cladocerans *Daphnia rosea*, *Diaphanosoma brachyurum* and *Bosmina lingirostris*, and the copepod, *Diaptomus kenai*. Other species are present though not ubiquitous (eg. *Daphnia middendorffiana*, *Diaptomus lintoni*), and species density is generally high (Liss and others 1995).

CONCLUSION

Hierarchical lake classification provided a tool to describe, define and increase understanding of the diversity existing in the high-mountain lakes of North Cascades National Park Service Complex. The classification can characterize data sets over multiple spatial scales that are appropriate to management or research questions being addressed. For this reason, the classification reflects interacting environmental features that constrain and define lake and watershed characteristics at multiple spatial scales. Climate and geology interact to form a physical template upon which lakes develop. Soils, vegetation, hydrology, aspect, and elevation interact to modify the developmental rate of local watershed and lake processes. The lake classification developed here was used to define the present physical, chemical, and biological states and characteristics of NOCA lakes and their watersheds. An attempt was made to identify proxies of capacity that would subsume all lake and watershed performances and allow ecologically meaningful interpretation for both the present and future. For this reason, development of the classification was an iterative process while attempting to understand a highly complex set of interacting physical and chemical variables. The classification was able to successfully order physical, chemical, and biological data with a limited set of lakes. If this approach to lake classification were applied to a more diverse landscape, a greater distinction between classes would be expected to result. Yet, from the research presented here, hierarchical lake classification was useful in identifying trends and significant differences among and between groups of lakes at three levels of spatial and temporal variability.

This classification offers a number of other potential applications. These include landscape interpretation, incorporation into Geographical Information System (GIS) databases, general water quality classification, identification of potential susceptibility of watersheds to anthropogenic impacts, classifications of lakes in other regions, and as a basis for monitoring programs. Park interpreters can use the classification to increase recreational user knowledge about landscape processes including lake formation, climatic patterns, and vegetational succession, to provide information about the relative persistence of lakes, and to describe lake ontological processes. As part of a GIS database for NOCA, the classification will be a useful management tool for natural- resource specialists to identify unique lakes or lakes of special concern based on flora, fauna, origin, size, or other criteria. The classification will also help identify the potential resiliency of lakes and their watersheds to user impacts (vegetation trampling, lake species alterations from salmonid stocking). The classification could be used to classify the range of water quality found within each vegetation zones or to act as a template for a similar approach to the classification of lakes in other regions. Finally, the data set can be incorporated into a monitoring program to address global warming during the next century.

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APPENDIX

APPENDIX I. Lake codes, acronyms and official USGS names. Unofficial names are in parentheses.

Park Code[1]	Acronym[2]	Lake Name
CP1	DOUB	Doubtful
DD1	JEAN	Jeanita
DD4	BOUC	Bouck
DD5	DD5	Unnamed (Upper Bouck)
DD8	DD8	Intermittent
EP2	EP2	Unnamed
EP3	EP3	Unnamed-Wilcox
EP4	EP4	Unnamed
EP5-1	EP5-1	Unnamed (Lower Wilcox/Sandy)
EP6	EP6	Unnamed (Upper Wilcox/Lily)
EP9-1	EP9-1	Stout Lake Pond
EP9-2	EP9-2	Stout Lake
EP10	EP10	Unnamed
EP11-1	EP11-1	Unnamed
EP11-2	EP11-2	Unnamed
EP12	EP12	Unnamed
EP13	EP13	Unnamed
EP14	EP14	Unnamed (Hidden Lk Tarn)
FP1	FP1	Unnamed
FP4	KLAW	Klawatti
FP5	FP5	Unnamed
FP6	FP6	Unnamed
FP7	MORA	Moraine
FP8	FP8	Unnamed
FP9	FP9	Unnamed
FP10	FP10	Unnamed
GM1	TRAP	Trapper
GM2	GNVW	Green View
HM2	HOZO	Hozomeen
HM3	RIDL	Ridley
HM4	WILL	Willow
LS1	LS1	Unnamed (Diobsud No. 1)
LS2	LS2	Unnamed (Diobsud No. 2)
LS3	LS3	Unnamed (Diobsud No. 3)
LS4	LS4	Unnamed
LS5	LS5	Unnamed
LS6	LS6	Ipsoot
LS7	LS7	Blum (Lower/West, No. 4)
M1	M1	Unnamed (Hi-Yu)
M4	M4	Green
M5	NERT	Unnamed (Nert)
M6	TTAR	Unnamed (Talus Tarn)
M7	M7	Unnamed (Lower Berdeen)

APPENDIX I,Continued.

Park Code[1]	Acronym[2]	Lake Name
M8	M8	Berdeen
M9	M9	Unnamed (Upper Berdeen)
M10	M10	Unnamed
M11	M11	Blum (Largest/Middle, No. 3)
M13	M13	Unnamed
M14	M14	Unnamed
M16	M16	Mt. Triumph (S)
M17	M17	Unnamed (Triumph)
M18	M18	Thornton (Upper)
M19	THRM	Thornton (Middle)
M20	THRL	Thornton (Lower)
M21	M21	Unnamed (Doug's Tarn)
M22	M22	Unnamed
M23	MONO	Monogram
M24-1	M24-1	Unnamed (Upper Quill)
M24-2	M24-2	Unnamed (Lower Quill)
M25	M25	Ice Fall
MA1	MA1	Unnamed
MA2	MA2	Silent (Upper)
MA3	MA3	Silent (Lower)
MC1	MC1	Blum (Small/North, No. 2)
MC2	MC2	Blum (Vista/Northwest, No. 1)
MC3	MC3	Unnamed
MC4	EGG	Egg
MC6	COPP	Copper
MC7	MC7	Unnamed (Kwahnesum)
MC8	MC8	Hanging
MC10	MC10	Unnamed (Ruta)
MC11	REDO	Redoubt
MC12	BEAR	Bear
MC13	MC13	Unnamed
MC14-1	MC14-1	East Lakes (Upper)
MC14-2	MC14-2	East Lakes (Lower)
MC15	MC15	Tiny
MC16-1	MC16-1	Middle (Upper)
MC16-2	MC16-2	Middle (Lower)
MC17-1	TAP1	Tapto (Upper)
MC17-2	TAP2	Tapto (Middle)
MC17-3	TAP3	Tapto (Lower)
MC17-4	TAP4	Tapto (West)
MC21-1	REVU	Reveille (Upper)
MC21-2	REVL	Reveille (Lower)
MC22	MC22	Unnamed
MC23	MC23	Unnamed

APPENDIX I, Continued

Park Code[1]	Acronym[2]	Lake Name
MC24	EILE	Eiley
MC25	WILE	Wiley
MC27	WILD	Wild
MC28	MC28	Unnamed
MC29	MC29	Luna
MC30	MC30	Unnamed
MC34	MC34	Unnamed
ML1	ML1	Unnamed (Sourpuss)
ML2	SWEE	Unnamed (Sweet Pea)
ML3	ML3	Unnamed (Torment)
ML4	VULC	Unnamed (Vulcan)
ML5	ML5	Unnamed
ML6	ML6	Unnamed
ML7	ML7	Unnamed
MLY1	MLY1	Unnamed (Upper Battalion)
MLY2	BATT	Battalion
MM1	MM1	Unamed
MM3	MM3	Unnamed (Last Chance)
MM6	WADD	Waddell (Lower/Sandalee)
MM7	WADM	Unnamed (Mid. Waddell)
MM8	MM8	Unnamed (Sandalee)
MM10	COON	Coon
MM11	MM11	Unnamed (Upper Rainbow, West)
MP1-1	MP1-1	Unnamed (W)
MP1-2	MP1-2	Unnamed (S)
MP1-3	MP1-3	Unnamed (N)
MP2	MP2	Unnnamed (Firn)
MP5	MP5	Unnamed (Big Beaver Pond)
MP8	MP8	Unnamed
MP9	MP9	Azure
MR1	MR1	Unnamed (Stilletto)
MR2	MR2	Unnamed (Twisp Pass Pond, N.)
MR3	MR3	Unnamed (Twisp Pass Pond, S.)
MR4	DAGG	Dagger
MR5	KETT	Kettling
MR6	KETU	Unnamed (Upper Kettling)
MR8	MR8	Unnamed
MR9	MR9	Unnamed
MR10	MCAL	McAlester
MR11	MR11	Unnamed
MR12	MR12	Unnamed
MR13-1	M131	Unnamed (Upper Rainbow, North)
MR13-2	M132	Unnamed (Upper Rainbow, South)
MR14	RAIN	Rainbow
MR15-1	MR15-1	Unnamed (Dee Dee/Tamarack)

APPENDIX I, Continued.

Park Code[1]	Acronym[2]	Lake Name
MR16	MR16	Unnamed
MS1	SILV	Silver
MS2	MS2	Unnamed
MS3	MS3	Unnamed
MS4	OUZL	Ouzel
MSH1	MSH1	Sulphide
MSH2	MSH2	Unnamed
MSH3	PRIC	Price
MSH4	MSH4	Unnamed
PM1	NONA	No Name
PM2	PM2	Unnamed (Skymo Pond)
PM3	SKYM	Skymo
PM4	SKYU	Unnamed (Upper Skymo)
PM5-1	PM5-1	Unnamed
PM5-2	PM5-2	Unnamed
PM5-3	PM5-3	Unnamed
PM5-4	PM5-4	Unnamed
PM5-5	PM5-5	Unnamed
PM5-6	PM5-6	Unnamed
PM12	PM12	Sourdough
RD2	THUN	Thunder
RD3	PYRA	Pyramid
RD4	RD4	Unnamed
RD5-1	PANU	Panther Potholes (Upper)
RD5-2	PANL	Panther Potholes (Lower)
SB1	SB1	Hidden
SM1	JUAN	Juanita
SM2-1	TRIL	Triplet (Lower)
SM2-2	TRIU	Triplet (Upper)

[1]Code used by North Cascades National Park Service Complex
[2]Acronyms used by present study